Hydrothermal processing of biogenic residues in Germany

A technology assessment considering development paths by 2030

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Abstract: The mining, processing, and use of finite natural resources is associated with significant interventions in the natural environment. Thus, these and other negative consequences make it necessary to reduce resource consumption. An important field of action is the more efficient use of biogenic residues as secondary raw materials. However, high water containing biomasses are still a problem since they need an energy- and cost-intensive pre-treatment for many conversion processes, which can make their use uneconomical. Hydrothermal processes (HTP) seem to be promising, since they require an aqueous environment for optimal processing anyway. Although technological progress within the industry is recognisable, however, to date HTP have not been established in industrial continuous operation in Germany. The core of this work is identifying reasons for this sluggish development and deriving appropriate recommendations for action.

Based on the hypothesis that HTP can contribute to the efficient utilisation of biogenic residues in the future, potentials and obstacles for the development of HTP in Germany are identified using a literature review, expert survey, expert workshop, and SWOT analysis. To estimate the future potential of HTP in a systematic and structured way, a multi-criteria technology assessment approach is developed based on the results. To this end, assessment criteria for HTP are derived, weighted by expert judgment, and integrated into a transparent and structured procedure. In addition, mainly based on a Delphi-survey key factors of HTP development by 2030 in Germany are identified and three development alternatives for HTP in Germany by 2030 are derived. Using a system analysis and a comparative multi-criteria analysis at plant level, these scenarios are analysed for their possible future impact.

Based on this methodology, the work shows that the production costs for the end products, the energy efficiency of the process, and the proportion of recycled phosphorus are of high relevance to the techno-economic success of HTP compared to reference systems, and they are therefore of high importance for its future development on the plant level. In addition, further key factors for the future development of HTP in Germany on the system level are found to be mainly in the political-legal (e.g. legal waste status of products from HTP) and techno-economic (e.g. cost-effective process water treatment) areas. According to this, important fields of action are the identification and use of cost reduction potentials (e.g. heat waste use), the development of system integrated decentralised plant concepts with integrated nutrient recycling (e.g. phosphorus), and the development of cost-effective ways to treat process water. System integration, cost-effective process water treatment, and nutrient recycling are all closely linked to production costs, investment costs, and potential revenues, and can contribute to improved process economics. For these areas, there is promising future potential to achieve higher competitiveness with reference technologies that are currently more economical.

Curriculum Vitae

Daniel Reißmann, born 08.08.1988, Grimma/Saxony, Germany

Education

1999-2007	Secondary school, Colditz and Grimma
2007	Graduation (A Level)
2008-2011	Bachelors study in Economics, University of Leipzig
2011	Bachelor of Science Degree in Economics
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2013	Master of Science Degree in Business Administration

Academic and professional experience

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Leipzig, den 04.10.2019

Daniel Reißmann

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List of Publications

This thesis is based on the following published papers, which are appended to the introductory chapters according to the following numeration:

Paper I

Reißmann, D., Thrän, D., Bezama, A. (2018) Hydrothermal processes as treatment paths for biogenic residues in Germany: A review of the technology, sustainability and legal aspects. Journal of Cleaner Production 172, 239-252. DOI: 10.1016/j.jclepro.2017.10.151.

Paper II

Reißmann, D., Thrän, D., Bezama, A. (2018) Techno-economic and environmental suitability criteria of hydrothermal processes for treating biogenic residues: A SWOT analysis approach. Journal of Cleaner Production 200, 293-304. DOI: 10.1016/j.jclepro.2018.07.280.

Paper III

Reißmann, D., Thrän, D., Bezama, A. (2018) How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal. Waste Management and Research 36(10), 912-923. DOI: 10.1177/0734242X18785735.

Paper IV

Reißmann, D., Thrän, D., Bezama, A. (2018) Key Development Factors of Hydrothermal Processes in Germany by 2030: A Fuzzy Logic Analysis. Energies 11, 3532. DOI: 10.3390/en11123532.

Paper V

Reißmann, D., Thrän, D., Bezama, A. (2020) What could be the future of hydrothermal processing wet biomass in Germany by 2030? A semi-quantitative system analysis. Biomass and Bioenergy 138. DOI: 10.1016/j.biombioe.2020.105588.

Paper VI

Reißmann, D., Thrän, D., Bezama, A., Blöhse, D. (2020) Hydrothermal carbonization for sludge disposal in Germany: A comparative assessment for industrial-scale scenarios in 2030. J Ind Ecol 2020;1–15. DOI: 10.1111/jiec.13073.

Related work has also been published in the following documents:

1) Reißmann, D., Thrän, D., Bezama, A. (2018) Is there a best way for the hydrothermal treatment of moist bio-waste? First experiences from a multi-criteria decision-making approach. EUBCE 2018 Papers of the 26th European Biomass Conference: setting the course for a bio-based economy. Extracted from the Proceedings of International Conference. DOI: 10.5071/26thEUBCE2018-3DO.9.2.

2) Reißmann, D., Thrän, D., Bezama, A. (2018) Hydrothermale Prozesse als Behandlungsverfahren für biogene Rest- und Abfallstoffe - Ein multikriterieller Bewertungsansatz. Konferenzband der Recy-Depotech.

Contribution to the Publications

The PhD candidate has made the following contributions to the appended papers summarized in the Table below. The authors' names are abbreviated as follows: Daniel Reißmann: D.R.; Daniela Thrän: D.T.; Alberto Bezama: A.B.; Dennis Blöhse: D.B.

Article	Authors Contributions
Hydrothermal processes as treatment paths for biogenic residues in Germany: A review of the technology, sustainability and legal aspects.	• Conceptualization, data curation, formal analysis, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking on the original draft as well as the edited versions, project administration and supervision were made by D.T. and A.B.
Techno-economic and environmental suitability criteria of hydrothermal processes for treating biogenic residues: A SWOT analysis approach	• Conceptualization, formal analysis, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking on the original draft as well as the edited versions, project administration and supervision were made by D.T. and A.B.
How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal	• Conceptualization, data curation, formal analysis, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking on the original draft as well as the edited versions, project administration and supervision were made by D.T. and A.B.
Key Development Factors of Hydrothermal Processes in Germany by 2030: A Fuzzy Logic Analysis	• Conceptualization, data curation, formal analysis, software application, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking of the original draft as well as the edited versions, funding acquisition, project administration and supervision were made by D.T. and A.B.
What could be the future of hydrothermal processing wet biomass in Germany by 2030? A semi-quantitative system analysis	• Conceptualization, formal analysis, data curation, model development and application, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking on the original draft as well as the edited versions, project administration and supervision were made by D.T. and A.B.
Hydrothermal carbonization for sludge disposal in Germany: A comparative assessment for industrial-scale scenarios in 2030	• Conceptualization, formal analysis, data curation, calculations, investigation, methodology, validation, any visualization and the writing of the original first draft and the edited final version were made by D.R. • Commenting and remarking on the original draft as well as the edited versions and checking data and calculations was made by D.B. • Commenting and remarking on the original draft as well as the edited versions, project administration and supervision were made by D.T. and A.B.

Contents

Part II Appended Articles

List of Acronyms

AHP	Analytical Hierarchy Process
APR	Aqueous Phase Reforming
C.I.	Consistency Index
C.R.	Consistency Ration
COD	Chemical Oxygen Demand
DDI	Data Documentation Initiative
FCM	Fuzzy Logic Cognitive Map(ping)
FDM	Fuzzy Delphi Method
GWP	Global Warming Potential
H	Hypothesis
HMF	Hydroxymethylfurfural
HTC	Hydrothermal Carbonization
HTG	Hydrothermal Gasification
HTL	Hydrothermal Liquefaction
HTP	Hydrothermal Processes
ISO	International Organization for Standardization
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
PNNL	Pacific Northwest National Laboratories
R.I.	Random Index
RQ	Research Question
SWOT	Strengths, Weaknesses, Opportunities, Threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VTC	Vapothermal Carbonization

List of Tables

This list only contains the tables of the introductory chapters, as the tables of the articles follow a different numeration and cannot be linked to this list.

List of Figures

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Part I

Introductory Chapters

1 Introduction and background

The extraction, utilisation, and processing of finite natural resources is associated with significant interventions in the natural environment and leads to emissions in water, soil, and air (UBA 2016). To reduce these negative consequences to an ecologically and socially acceptable level, various strategies are pursued for a more environmentally friendly and efficient use of natural resources in production and consumption. For example, in the Roadmap to a Resource Efficient Europe, the European Commission focuses on increasing resource productivity, decoupling economic growth from resource use, strengthening competitiveness, and promoting security of supply (European Commission 2011, Staffas et al. 2013). In the current version of the German Resource Efficiency Program, the German government aims to secure a sustainable supply of raw materials, increasing resource efficiency in production, designing resources and products more efficiently, and developing a resource-efficient circular economy (BMUB 2016).

The circular economy has a key role in reducing the consumption of natural resources. In such an economy, the prevention of waste (longevity, reuse, ease of repair, etc.) comes first, followed by recycling and energetic use (EPRS 2017). Besides the circular economy, the bio-based economy focuses on the production of renewable biological resources and their conversion into food and feed, bio-based products, and bioenergy (European Commission 2012). The bio-based economy considers the transformation to a circular economy as an essential guiding principle. In terms of resource efficiency and sustainability, it aims at the gradual exploitation and multiple uses of natural resources (BMEL 2014). Hence, measures of the circular and the bio-based economy are closely related and should support each other in achieving their goals.

The efficient usage of biogenic residues and waste (e.g. landscaping materials, sewage sludge, and animal excreta) is an area in which the potential synergies between the two strategies are particularly clear. In terms of the circular economy, waste is reduced and converted into potentially valuable products. Material applications in particular are currently of high interest, as materials for various fields of applications can be produced (e.g. chemicals, construction materials) (UBA 2014). This results in the substitution of products based on finite, mostly fossil resources (such as petroleum) with bio-based products, which also supports the principles of the bio-based economy. In Germany, the energetic use of biogenic residues has predominated in recent years. For example, in biogas plants, these residues are anaerobically converted to biogas, which is then burned in combined heat and power plants to produce energy and heat. Functionalised compounds such as carbohydrates, proteins, and fatty acids are lost. In addition, around half of the carbon in the residues is lost as carbon dioxide (Pleissner 2017). Thus, such a use of biogenic residues is not completely efficient, not because of the technical process, but because the material potential of the biomass is not used.

What is needed are processes that make the best possible use of both the material and energy potential of the available residues. First, this makes a valuable contribution to climate protection, as climate-neutral fuels produced with residues can replace fossil fuels. Second, the principles of the circular and the bio-based economy are also considered, as the material use is the primary application. Another advantage of the efficient use of biogenic residues and waste is that there is no competition to food and feed production (e.g. land competitions), as it is not a crop biomass (Baur 2010). Finally, residual materials have to be disposed of anyway, so a more efficient treatment can save disposal costs and therefore also represents an interesting option from an economic perspective (Mühlenhoff 2013).

The potential for not or inefficiently used biogenic residues is likely high. A recent study estimates a technical potential in Germany of 98.4 million tons of dry matter. Of this dry matter, 67.4 million tons are in material or energetic use, while about 30.9 million tons either are not used or have unknown usage (Brosowski et al. 2016). The technical potential includes that part of the theoretically available quantity that can be sustainably taken from a given area or region, under consideration of a number of limiting factors (i.e. availability, ecological limits, technical constraints, temporal and spatial imbalances between supply and demand) (Kaltschmitt et al. 2009). Because the data for some material flows is insufficient, the actual potential may be even higher. In addition, if currently inefficiently used residues (e.g. energy use without prior material use) are considered, the biomass potential for correspondingly more efficient utilisation paths is presumably also higher (Brosowski et al. 2016).

Due to the situation described above, treatment processes which make the best possible use of the potential of biogenic residues as sources of chemicals, materials, and energy are currently being investigated (cf. Fricke et al. 2012, Mahro & Timm 2007). The options include various biological (e.g. fermentation) and chemical (e.g. pyrolysis) processes that can be specifically optimised to treat residuals (e.g. Guven et al. 2019, Tröger et al. 2013). However, a problem area is high water-containing substrates. Apart from anaerobic digestion, they are not suitable for any of the processes discussed without pre-treatment, since a certain dry fraction in the substrate is often necessary for optimal processing (e.g. for fast pyrolysis, gasification) (Crocker 2010, IEA Bioenergy 2011). If this is not the case, costly drying processes are necessary, which can significantly reduce the energy efficiency of the overall process and therefore make it uneconomical (Haque & Somerville 2013, Doering & Larson 2012).

To avoid costly and energy-intensive substrate pre-treatments, hydrothermal processes (HTP) are currently discussed as suitable conversion options. Since they require an aqueous environment for optimal processing, they seem to be well suited for wet substrates (Tekin et al. 2014). The following sections introduce hydrothermal processes and present the state of the art and knowledge on HTP worldwide and particularly in Germany. Based on this, knowledge gaps and the corresponding objectives of this work are subsequently explained.

Hydrothermal processes: Introduction and status quo

In the technical context, the term 'hydrothermal' refers to a reaction with hot, liquid water under pressure (Vogel 2016). In 1913, Friedrich Bergius first described how such a reaction can be used to produce a coal-like product from biomass by imitating the geological process of brown coal formation within a few hours (Bergius 1913). Following this pioneering work, in 1971 the first fundamental study on the use of hydrothermal conditions for biomass liquefaction was published at the Pacific Northwest National Laboratories (PNNL) in the United States (Appell et al. 1971). Shortly thereafter, the first technical concepts for hydrothermal biomass gasification were developed (Modell et al. 1978, Modell 1982). At the beginning of the millennium, the hydrothermal reaction principles were rediscovered (e.g. Cui et al. 2006) and since then have been constantly evolving. Today, the following types of HTP are distinguished as presented in Table 1.1.

Table 1.1. Types of hydrothermal processes (own composition)

Processing type	Description
Hydrothermal carbonisation (HTC)	Hydrothermal carbonisation usually takes place at temperatures of 160 to 250 °C, a pressure of 10 to 30 bar, and reaction times of about 1 to a maximum of 72 hours (Kruse et al. 2013, Vogel 2016). High-temperature HTC uses temperatures of 300 to 800 °C (Hu et al. 2010). The process mimics the natural process of brown coal formation and produces a corresponding coal-like end product.
Hydrothermal liquefaction (HTL)	Hydrothermal liquefaction produces biogenic oils at predominantly subcritical conditions. This corresponds to temperatures of 220 to 400 °C, pressure conditions of 40 to 200 bar, and reaction times of a few minutes (Peterson et al. 2008). At temperatures above 250 °C, higher energy yields can be achieved in the product. The addition of catalysts is more common for this type of process than for HTC. Mostly alkaline salts are applied (Huber et al. 2006).
Hydrothermal gasification (HTG)	Hydrothermal gasification is divided into three sub-reactions. Subcritical HTG takes place at 280 to 374 °C with a maximum pressure of 221 bar and mainly produces methane. Supercritical HTG takes place from 375 to 800 °C at a pressure of more than 221 bar. In particular, hydrogen is generated in this reaction. Both reactions only need a few seconds. A special case is the aqueous phase reforming (APR), which takes place at 200-280 °C, a pressure of 15-50 bar, and a few hours' residence time. Here, mainly hydrogen, carbon dioxide, and alkane are generated (Hrnčič et al. 2016). An addition of catalysts is recommended. In most cases, metal catalysts and alkaline salts are used (Kruse 2009).

For all three conversion paths, the molecular size of the substrates is reduced and / or the oxygen content in the final products is minimised. As a result of the lower oxygen content, the calorific value of the products increases, which is why they are generally well suited as climate-neutral fuels. In addition, the proportion of water in the end products is strongly reduced compared to the substrate, which also increases the energy content in the product (Vogel 2016).

Water is the central reaction medium of all processes described. At high temperatures and pressures, called subcritical or supercritical conditions, highly compressed water acts as a solvent, reactant, and catalyst (Hrnčič et al. 2016). As shown in Table 1.1., especially pressure, temperature, and reaction time determine which product composition results from hydrothermal conversion. Even if the desired main product is solid, liquid, or gaseous, all three states of aggregation are produced in different compositions depending on the type of process. Furthermore, the compositions differ considerably based on the specific process conditions and the substrate used (cf. Román et al. 2018, Salimi et al. 2016, Onwudili et al. 2013).

Depending on the type of process, the respective main product in the largest mass fractions and the best possible product properties (e.g. high energy and carbon contents) is always desired, which is why researchers are currently intensively analysing corresponding optimal process conditions (Zhao et al. 2018). Furthermore, the optimal handling of by-products is also under investigation. One focus is the efficient treatment of the liquid phase from HTC. This process water is particularly heavily loaded with organic compounds and reaches for the sum parameter of all, under certain conditions oxidisable substances (COD), a very high value of up to 68,500 milligrams of oxygen per litre (Vogel 2016). A direct inlet of the process water is therefore not permitted, so it must be cleaned. Various options are currently being discussed in this regard, such as process water cycles, wet oxidation, and membrane processes (e.g. Makälä et al. 2018, Stutzenstein et al. 2018, Kühni et al. 2015). By contrast, the undesirable by-products from the HTL and HTG are much less burdened, which is why they are currently not the focus of research.

In addition to the potentially high energy contents, the energy efficiency, and the simple processing concepts with fast reaction times, the potentially high carbon contents of HTP products are also advantageous. For example, the carbon efficiency – that is, the proportion of carbon in the substrate that is later included in the usable end product – is high. For instance, HTC achieves values of up to 95% (Vogel 2016), while the value of anaerobic conversion to biogas is only 50%. As a result, much less carbon dioxide is emitted during the hydrothermal conversion of biomass, which contributes to a more favourable greenhouse gas balance (MPIKG 2006).

Due to the high carbon content in the product, the solid product of HTC is also potentially useful as soil conditioner and for carbon sequestration (Breulmann & Fühner 2014). However, the application options for products made by HTP are even more diverse, as shown in Table 1.2.

Table 1.2. Fields of application for products from hydrothermal conversion (own composition)

HTP products	Fields of application	References
Main product from HTC		
Solid coal-like product	• Energy production • Energy storage • Carbon storage • Soil conditioning and fertilisation • Carbon additives • Concrete additive • Road coverings • Application as adsorbent • Application as catalyst • Application as electrode material • Refining to platform materials (e.g. furfural, hydroxymethylfurfural (HMF))	Román et al. 2018; Wu et al. 2017; Rillig 2010; Aida et al. 2010, Qi et al. 2008; Kruse & Dahmen 2018; Vogel 2016
Main product from HTL		
Bio-crude	• Energy production (especially thermal use) • (Upgraded) hydrocarbon biofuels • 'Drop-in fuels' • Refining to platform chemicals (e.g. phenols, aldehydes, organic acids)	HyFlexFuel 2017; Vogel, 2016; Elliot et al. 2015; Xu et al. 2014
Main product from HTG		
Synthetic fuel gas	• Energy production • Biofuel gases • Integrated algae cultivation • Combined applications (e.g. with fuel cells)	Elsayed et al. 2014; Elliot et al. 2009; Wan 2016

The variety of products and applications is one specific advantage of HTP, as it can be used for different material and energetic purposes. In addition, the products also have a relatively high quality compared to those from other thermochemical processes (e.g. regarding calorific value, ash composition, tuneable surface functionalities, presence of natural binders, conductive behaviour) (Román et al. 2018).

Currently, most HTP-related activities are limited to research. However, the upscaling of the technologies is also being developed. Pilot and demonstration plants for the different types of processes exist, for example, in Germany, Denmark, Switzerland, Italy, Japan, the United States, and China (cf. Kruse & Dahmen 2018, Vogel 2016). Larger HTC plants are operated by Ingelia in Valencia (Italy) and AVA Biochem in Zug (Switzerland) (Hernández 2011, Hitzl et al. 2015, AVA Biochem 2015). HTL pilot plants are located, for instance, in Albany (USA) and Aalborg (Denmark) (Kan & Strezov 2015, Castello et al. 2018), and new pilot plants have also recently been put into operation at the PNNL (Elliot et al. 2013). Furthermore, an HTG test facility that has already been in operation for some time is that of the Chugoku Electric Power Company and the University of Hiroshima in Japan (Matsumura 2015).

Although technological advances within the industry are evident from the growing number of patent applications in this field (De Mano Pardo et al. 2016), so far HTP has not been established at an industrial scale, which is shown by the fact that hardly any plants exist in industrial and commercial continuous operation. However, the Terranova Energy HTC plant in Jining, China (Terranova Energy 2016) is currently being expanded to a large-scale level and is expected to be able to utilise around 40,000 tons of sewage sludge (dry matter) in the future.

Recent pioneering work on HTP comes, to a large extent, from Germany. In 2006, the Max Planck Institute for Colloids and Interfaces published a study (Cui et al. 2006) which garnered scientific interest in the re-discovery of HTP. Following this, the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt) sponsored several research projects on HTP between 2007 and 2016, with a focus on HTC (Rekate et al. 2017, Grimm 2013). To date, research in this area has been highly active with an upward trend (cf. Kruse & Dahmen 2018).

Based on these research activities, first technical applications have been developed and companies founded. For example, a cursory examination of the entries in the commercial register shows that most of the HTP companies in Germany were founded around the year 2008. Some have since disappeared from the market, but several pilot and demonstration plants have nevertheless been installed in Germany. Table 1.3. gives an overview of the current state of knowledge on existing HTP plants in Germany. It should be noted that due to a lack of up-to-date references, there is the possibility that some of the listed plants are no longer in operation. In addition, the facilities may be modified or further developed before the publication of this work.

Table 1.3. HTP pilot and demonstration plants in Germany (own composition)

Manufacturing company and plant location	Plant specification	References
Karlsruhe Institute for Technology, Karlsruhe	HTG pilot plant (VERENA) with a biomass capacity of 2 tons per day (max. 20 % dry matter content). The plant usually operates with 660 °C and 28 MPa. Potassium bicarbonate or Potassium carbonate is usually added as a catalyst. Products are carbon dioxide, hydrogen, ethane, methane, and traces of carbon monoxide.	Möbius et al. 2012, Boukis et al. 2007, Boukis et al. 2006
Grenol GmbH Kalkar/Niederrhein	Industrially applicable HTC base module with a throughput of 10 tons of biomass per day (20-30% dry matter content). The HTC process takes place at a temperature of about 230 °C and about 25 bar	Grenol GmbH 2016

	pressure. After a residence time of 3 to 6 hours, the resulting coal is cooled and discharged from the pressure vessel. Subsequently, the resulting coal, water, and sludge are separated and further processed.	
Suncoal Industries GmbH, Ludwigsfelde near Berlin	HTC pilot plant which runs in batch mode or continuous operation for campaigns. It comprises six central units, including HTC module, cooling system, membrane pressure filter press, technical peripherals, and automation and measurement technology. The HTC reactor operates at 260 °C and 47 bar.	Suncoal Industries GmbH, 2019
Terranova Energy GmbH, Kaiserslautern (near waste water treatment plant)	HTC pilot plant with continuous stirred reactor for the processing of sewage sludge (15-30% dry matter content). The plant is in a container construction and can utilise the sewage sludge of up to 30,000 inhabitants. Currently, the operation is based on campaigns.	Terranova Energy GmbH 2017
AVA-CO2 AG (HTCyle), Karlsruhe and Relzow/Anklam	The biomass (max. 25% dry matter) is premixed with recirculated process water at 160 °C and converted in multi-batch operation at more than 220 °C. The HTC plant ('HTC-1') in Relzow converts 8,000 tons of biomass into 2,664 tons of solid product per year. These values relate to the first phase with two HTC reactors, whereas 48 reactors are planned as final equipment. The HTC process works here at 24 bar and 210 °C and requires a reaction time of 3 to 5 hours.	Anderer 2012, Kusche & Ender 2018
REVATEC Research Centre Geeste	HTC and VTC small-scale research reactors. However, Revatec also offers commercial equipment. In addition to the reactors and heat storage systems, all necessary peripheral components such as waste air and water treatment, process systems, and product packaging are provided in the plants. The specific parameters required for carbonisation of the biomass are adjusted on a case-by-case basis. The plants mainly use biogenic residues.	Revatec 2011
CarbonSolutions, Kleinmachnow/Teltow	HTC demonstration plant which is approved for 10,000 tons of biomass input per year. The system is driven on a campaign basis for individual customers. At approx. 200 °C and 20 bars, a carbon-water suspension is produced in a reactor and then dried. The plant mainly uses foliage and green waste from the Greater Berlin area as substrates.	Schnell 2012
Artec Biotechnology GmbH, Halle	Campaign-wise operation of an HTC demonstration plant by Hallesche Wasser and Stadtwirtschaft GmbH as part of a research project. The temperature of the process is between 200 and 220 °C with an average residence time of 5 hours. The biomass used has a water content of max. 50%. The aim is to produce around 1,111 tons of solid product with 2,500 tons of biomass input.	Blümel et al. 2015

State of the art in the research field and knowledge gaps

Currently, HTP research is focusing on individual technological and process engineering areas, with an emphasis on demonstrating economic feasibility. For example, Wilk et al. (2019) have examined how to derive optimal process properties for particular targets (e.g. identifying the most suitable substrates). These authors recommend using the solid product from HTC generated by sewage sludge especially for co-incineration. Further research has examined the most cost-effective solutions possible for the utilisation of polluted process water from hydrothermal carbonisation. For example, Fettig et al. (2018) propose a multi-stage process consisting of an optional nutrient recovery, an anaerobic purification stage, an aerobic post-treatment, and a final treatment with ozone or activated carbon. Furthermore, there are recognisable research priorities regarding the life cycle assessment of certain HTP chains (e.g. Meisel et al. 2019) and techno-economic analyses of specific applications of HTP (e.g. Ranganathan & Savithri 2019).

In practical testing, much of the research is limited to laboratory or pilot-scale trials. In contrast, results relating to industrial continuous operation are scarcely available at present. This can be explained by the fact that there is a lack of such systems (see previous section). There is high interest in obtaining information on the holistic classification of HTP in industrial continuous operation (Reißmann et al. 2018b), but in many cases, this research first has to relate to fictitious modelling (modelled upscaling, for example, from the pilot scale), as can already be seen in some current work (Elliot et al. 2013). However, individual extrapolations to process characteristics or individual life cycle assessments on an industrial scale will not be sufficient to allow a holistic classification of HTP compared to reference systems, as only partial areas are considered.

Thus, there is a research gap here, because holistic methods for the techno-economic, social, or ecological assessment of HTP barely exist. The only known work in this field is from Suwelack (2016), and it is limited to HTC. Suwelack (2016) developed and tested a standardised assessment method for bio-refinery technologies for model equations of HTC. In concluding the paper, the author mentions the need for further research in this area, in particular regarding the identification of evaluation criteria and their weighting in the context of a multi-criteria evaluation, which should be developed with the involvement of various stakeholders. The present work aims to address this knowledge gap and wants to cover the issue of a so far missing holistic multi-criteria evaluation approach for HTP. In part, it also seeks to derive assessment metrics for HTP and to weight those using expert judgments, which is also a gap in knowledge currently.

Another research gap can be seen in the analysis of future developments of HTP. Currently, the only recommendations for a future system contribution of HTC and HTL in Germany with a specific time horizon are those by Weidner and Elsner (2016). However, they do not conduct a structured and empirically based analysis, but instead mainly use corresponding literature and derive some basic statements. For example, they recommend the use of the solid product from HTC as an energy carrier, soil additive, and industrial carbon carrier. In general, Weidner and Elsner (2016) suggest concentrating on nutrient recycling more strongly, and on corresponding research and development in future. From a scientific perspective, however, a structured and methodologically robust analysis of the future development pathways of HTP using established methods (e.g. scenario analysis) is still lacking. In addition, there is still a dearth of information on key development factors for HTP in Germany, both at the system and the individual plant levels. Therefore, the present work also aims to contribute to developing this knowledge by analysing the system level with a scenario approach that was not applied for this field of research so far. Regarding the gap in knowledge on future-oriented analysis at the plant level, it is intended that a tailored technology assessment instrument is to be applied for different scenarios.

Finally, it can be stated that this work addresses two knowledge gaps. First, the so far missing holistic analysis and corresponding method on the potentials of HTP as a treatment technology for wet biomass and second, the hitherto missing future-oriented analysis of the development chances and risks of HTP in Germany by means of a structured analysis.

Objective and research framework

Based on the situation in Germany and the gaps in knowledge identified above, the main objective of this work is to systematically analyse the most important potentials and obstacles regarding the development of HTP for biogenic waste treatment in Germany using a holistic assessment approach, and to provide a series of recommendations to foster these potentials and reduce barriers for future development. As the target year 2030 was chosen, since the analysis focuses primarily on short-term development effects for HTP and therefore a time horizon that is longer than 2030 can only be estimated with very high uncertainties, which in turn reduces the validity of the results. Due to the fact that there is no market for HTP in Germany currently, it is also unclear whether the technology still exists in Germany beyond 2030, which also largely excludes a far-reaching time reference.

Table 1.4. presents the two research questions (RQ) and six underlying hypotheses (H) which set the research framework in correspondence with the described objective.

Table 1.4. Research questions and associated hypotheses (own composition)

Research questions	Associated research hypotheses
RQ1. What are key barriers and potentials for HTP as biogenic treatment options in Germany so far? What are key assessment metrics that can be derived from this? How can they be set into an evaluation framework to estimate the techno-economic competitiveness of HTP concepts compared with each other and reference systems?	H1. HTP are suitable future technologies for the utilisation of so far unused biogenic residues in Germany, if techno-economic, ecological, and legal barriers in particular can be overcome and specific potentials of the technology can be used most efficiently. H2. Especially if techno-economic uncertainties can be reduced and optimally eliminated, the application of HTP as treatment options for biogenic residues will become likely. H3. Techno-economic uncertainties can be reduced if stakeholders (e.g. technology developers, researchers, technology users, product users, policy makers) are able to compare different HTP concepts and paths with each other and with reference systems regarding their current and future potential by considering multiple key metrics. H4. If a tailor-made technology assessment approach considering multiple key criteria is available, the current and future potential of HTP under certain conditions and compared to reference systems will be easier to estimate.
RQ2. What are key factors for the development of HTP in Germany as efficient treatment technologies for biogenic residues by 2030? Which future paths are based on these factors and particularly promising considering multiple key metrics (regarding RQ1)?	H5. For the successful development of HTP by 2030 in Germany, some key factors are of very high importance. H6. If these key development factors are combined in different scenarios and assessed comparatively while considering multiple evaluation criteria, this will help to derive the most promising future development paths at the system and industrial-scale plant levels.

This work contains six articles (cf. p. IV and Part II) that contribute to the validation/falsification of the above hypotheses and to the answering of the research questions. Table 1.5. gives an overview of how the papers address the hypotheses.

Table 1.5. Main content of the research articles and connection to the research questions (own composition)

Paper	Addressed hypothesis	Main content
I	H1, H2	This paper presents a comprehensive literature review on technological, economic, political-legal, and ecological potentials and obstacles of HTP in Germany and derivation of research gaps.
II	H2, H3, H4	Based on the information from Paper I, an expert survey, and an expert workshop, the potentials and obstacles of HTP are further underpinned and structured as part of a SWOT analysis. Based on this, criteria for the multi-criteria evaluation method are derived.
III	H4	This paper covers the systematic development of the multi-criteria technology assessment approach for HTP. Methodologically, a structured review is conducted in which suitable multi-criteria decision analysis (MCDA) methods for HTP are analysed and compared. On that basis, a tailor-made method is recommended.
IV	H5	Based on the information from Papers I and II as well as a Delphi survey conducted among 51 national and international HTP experts, key factors of HTP development until 2030 are identified by means of fuzzy logic.
V	H5, H6	Based on the results of Papers I and IV, fuzzy cognitive mapping (FCM) is used to generate three future scenarios for HTP in Germany by 2030. These are analysed by means of soft-computing their effect on other important key factors to derive system relationships and initial recommendations for action (system level analysis).
VI	H5, H6	Based on a modelled reference case on industrial-scale HTC for sewage sludge disposal, the three scenarios are analysed regarding their effect on the plant level. For this evaluation, the multi-criteria method developed in Paper III is used and first validated. In addition, this paper considers how efficient (i.e. in terms of MCDA) the HTC cases are compared to a conventional status quo treatment (i.e. thermal drying of the sewage sludge) and what recommendations can be derived from this regarding HTC technology development in this area (plant-level analysis).

Expected value added of this work

With regard to the current state of knowledge and according to the stated objective, the intended novel contributions of this work are as follows:

(i) Derivation of key evaluation metrics for HTP in Germany at the industrial-scale plant level, and their transfer into a transparent assessment procedure based on established methods but tailored to HTP assessment.

(ii) Derivation of key development factors for HTP and scenarios for HTP development in Germany by 2030.

(iii) System-level analysis of scenarios derived from the key development factors.

(iv) Test application of the assessment procedure developed in (i), assuming industrial-scale HTP plants based on the scenarios developed in (ii).

(v) Derivation of recommendations for HTP stakeholders based on a forward-looking analysis that incorporates multiple evaluation criteria.

The methods and results section are both structured according to these intended contributions to clearly show the connections among them.

Next, Chapter 2 covers the methodology used to derive the mentioned intended contributions of this work. Chapter 3 then briefly shows the results and recommendations and gives a short discussion on these results. Chapter 4 gives a conclusion and a future outlook for this work.

2 Materials and methods

To structure the work and ensure its consistency, this chapter presents the methodological steps in relation to the intended novel contributions of this work stated in the last sub-section of Chapter 1 (cf. expected value added of his work). The sections of this Chapter are therefore also named similar to the aforementioned intended novel contributions (i) to (v)

Derivation of HTP evaluation metrics and technology assessment tool

To develop a comprehensive information and data base for the several following steps, primary and secondary information on the current potentials and barriers of HTP in Germany was first collected and structured. In doing this, the focus was on primary information using empirical methods, as there is little or no secondary information available on some thematic issues concerning this dissertation (e.g. evaluation criteria for HTP). This information and data on the current situation were used in various phases of this work. Table 2.1. summarises the steps of the investigation.

Table 2.1. Methods used to research the current situation of HTP in Germany (own composition)

Method	Number of participants/ reviewed references	Date	Brief description of content	Paper of origin[1)]	Info. used for paper[1)]	Primary data availability[2)]
Review on HTP	120 reviewed references	01/18	A modified content analysis was conducted along the categories of technology, economy, environment, and law with regard to potentials and obstacles as well as future research needs of HTP in Germany.	I	II, IV	No primary data collected.
Focus group	41 participants	09/16	The group openly discussed general information on technological, economic, environmental, and legal potentials and barriers of HTP concerning the management of biogenic residues. Participants were mainly researchers, technology developers, and technology users from Germany and Switzerland.	II	IV, V	Results and photo protocol on request.
Expert survey	22 requests, 18 responses	09/16	The expert survey consisted of 13 open questions about technological, economic, and environmental potentials and barriers of HTP for the treatment of biogenic residues in Germany. Participants were feedstock suppliers, technology developers, technology users, retailers, product users, policy makers, and researchers.	II	IV, V	DDI[3)] conform data documentation on request.

[1)] Numbering of papers according to page VI.
[2)] All primary sources are anonymised and thus contain no personal information.
[3)] DDI: Data Documentation Initiative (DDI 2018).

As mentioned, the basis information was used for several papers in this work. In addition, however, further up-to-date and relevant information was identified for each specific step, so the individual articles always refer to the latest available knowledge.

Based on the potentials and barriers regarding HTP as technologies for the treatment of biogenic residues in Germany, specifically tailored assessment criteria were derived. The aim was for the evaluation criteria to be objective, consistent, customisable, transparent, and non-redundant. It was also important for them to have little or no influence on each other and for data to be available (Rohweder et al. 2015). Although criteria for technology assessments are highly relevant, their selection is often relatively unstructured and performed by a limited number of stakeholders. To increase the objectivity and transparency of the criteria and to assess their importance for evaluation, a structured approach is generally recommended and was therefore used in this work. Namely, the evaluation criteria were derived using a SWOT analysis (Kotler et al. 2010) based on the potentials and barriers identified in the previous methodological step. Based on this analysis, a subsequent derivation of objectives was performed, and their assignment to established criteria for technology assessments from corresponding references was checked (cf. Reißmann et al. 2018b). To derive the criteria based on the strengths, weaknesses, opportunities, and threats of HTP, qualitative goals were first derived from the principles listed in Table 2.2.

Table 2.2. Target derivation principles based on a SWOT analysis (own composition)

Target category	Target derivation principle
Targets considering strengths and opportunities	Follow opportunities that fit the strengths
Targets considering strengths and threats	Use strengths to counteract threats
Targets considering weaknesses and opportunities	Eliminate weaknesses to use new opportunities
Targets considering weaknesses and threats	Develop defences to avoid weaknesses becoming the aim of threats

The following principles were used to select criteria:

1. Only those criteria are chosen that were applicable to at least one target, and
2. The chosen criteria are modified (if needed) with regard to the corresponding target.

The selection procedure for the criteria is flexible and can be applied to a range of selection cases. The corresponding rules for the final selection of the criteria can also be varied on the basis of the individual case and do not necessarily have to correspond to the above. The assignment of the criteria to the targets can be visualised with an arrow diagram. This is especially recommended for structuring with a large number of goals and potential criteria. Depending on the objective of the further evaluation, the selected criteria can still be underpinned with information. This may include an assignment to a particular type of criterion (input, output, knockout criterion), information on units, assignment of minima and maxima (e.g. limits), and target values and/or ranges. In this work, an assignment of criterion type is made and units are specified. An indication of minimum, maximum, or target values is checked individually and only determined if this appears expedient for the corresponding criterion (e.g. to comply with certain legal requirements or due to technical restrictions) (e.g. Grandt 2015, Srdjevic et al. 2012). The advantages of the described procedure for deriving suitability criteria of the technologies are the high transparency (e.g. structured and traceable method) and objectivity (e.g. inclusion of expert knowledge). In addition, the criteria ultimately relate to both the benefits and drawbacks of HTP, as all dimensions of the SWOT analysis are included. This can prevent a positive or negative tendency in the selection of criteria.

Based on the procedure described above, in this work the evaluation criteria for HTP listed in Table 2.3. were derived to serve as metrics for an HTP technology assessment. It has to be mentioned that this list was originally developed in Reißmann et al. (2018b), however, in the referenced publication there was a communication mistake with the publisher so that the Table in this article has no differentiation between types of criterion. Hence, the author wants to emphasize using the following Table as reference for the criteria list and not the Table in the mentioned article.

Table 2.3. Long-list on HTP assessment/suitability criteria (own composition)

Criteria	Definition	Unit
K.O. criterion (Fulfillment must be given for every assessment alternative)		
Dry matter content of substrates	The relation of organic dry matter to water content of the substrate. An organic dry matter content between 10 to 30 % for optimal processing is recommended. If this range is not fulfilled the substrate is not suitable and hence the alternative may be excluded from the analysis.	Percent of organic dry matter content
Input metrics (to be minimized)		
Production costs	Raw material costs and manufacturing costs of the product at least (e.g. solid product from HTC). For the case studies in paper VI also investment, operating and staff costs are included.	Monetary unit per functional unit
Distance to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Distance unit
Pollution of process water	Share of organic substances in residual water that occurs after hydrothermal processing.	mgO_2/L (COD value)
GHG emissions	CO_2 emissions occurring through the process steps relating to the system boundaries.	Global Warming Potential
Output metrics (to be maximized)		
Technology Readiness Level	Classification of the level of development of a considered technology according to ISO 16290.	Scale from 1 to 9
Material efficiency	Relation of product output to raw material input.	Percent
Energy efficiency	Relation of energy output to energy input.	Percent
Calorific value of product	Maximum usable heat amount through the combustion of the end-product (coal, oil or gas).	Mega Joule (MJ) per functional unit
Carbon share of end-product	Share of carbon in HTC solid end-product in relation to total mass volume.	Percent
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in.	Percent

Table 2.3. provides a criteria ‘long list’. Depending on the purpose of the evaluation, the technologies considered, and other framework conditions, however, it could be that only a selection of criteria has to be used (‘short list’). A decision tree is suitable to select criteria (cf. Kamiński et al. 2018, Reißmann et al. 2018c), but another possible option is verbal argumentation (e.g. like in Paper VI).

The technology assessment approach was developed specifically for the evaluation of HTP as conversion technology for moist biogenic residues. The central aim was to integrate the assessment criteria into a transparent, adaptable, and systematic multi-criteria assessment approach for HTP that would be applicable for modelled scenario-based case studies to derive recommendations for action. This is further explained in the forthcoming sections.

The developed procedure is iterative; hence, one can return to a previous step at any time in the procedure and, if necessary, make adjustments, changes, and additions.

This is particularly helpful if the evaluation reveals problems that have not yet emerged in previous steps. Figure 2.1. shows the flowchart.

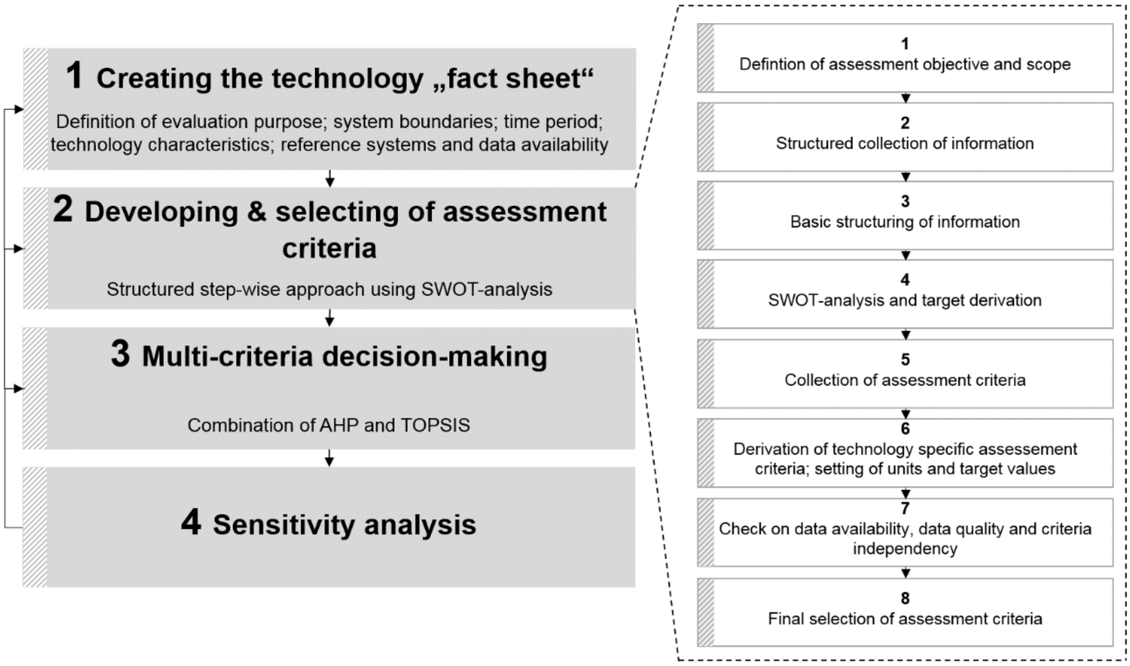

Figure 2.1. Sequence of the technology assessment approach for HTP (own illustration)

Step 1 of the outlined process entails describing the technologies, facilities, or processes to be assessed with a ‘technology fact sheet’. To achieve consistent, interpretable, and transparent results, it is recommended that the fact sheet contain information on the evaluation purpose, system boundaries, considered time period, basic characteristics of considered technologies, reference system(s), data availability, and quality of available data.

The system boundaries are defined with regard to the process chain of HTP. This includes (1) feedstock and collection, (2) preparation, transport, and storage, (3) conversion and refinement, (4) product distribution, (5) product usage, and (6) end-of-life. Depending on the evaluation purpose, some process steps may be excluded, which further reduces the evaluation effort (e.g. for data generation). The definition of the considered time period is especially important regarding data availability and evaluation purpose. The description of the basic technology characteristics (e.g. used substrates, process parameters, etc.) is needed to increase transparency and interpretability of the results and to check whether the technologies are generally comparable (e.g. regarding plant capacity). Including reference systems is necessary to set a comparative scale, which is why it is recommended that at least one such system be included in the evaluation. However, depending on the evaluation purpose, sometimes this is not necessary (e.g. if just HTP plant alternatives are compared). The check on data availability and quality is already crucial at the start of the assessment.

For example, if some data is not available or if data quality is insufficient, assessment alternatives or process steps must be excluded from the evaluation, or other assumptions have to be made.

Step 2 of the technology assessment procedure includes the derivation of assessment criteria, as previously discussed. In this work, the criteria listed in Table 2.3. were used. However, using the illustrated approach (cf. Figure 2.1, right hand side), the criteria could be adapted if new information and/or further data is available.

The multi-criteria analysis (MCA) takes place in **step 3** of the overall process. The MCA approach was developed in particular on the basis of the review of multi-criteria decision-making instruments in the field of bio-waste management. First, it was Ganzexamined whether an already existing multi-dimensional assessment method could be directly transferred to HTP assessment. Based on recommendations and procedures published by Billig (2016), DFG (2013), Ganzevles and van Est (2012), and Scheffzcik (2003) the following requirements for the HTP assessment procedure were considered: transparency, consistency, transferability, holistic nature, multi-dimensionality, applicability, objectivity, and adaptability. Considering these requirements, a combination of the Analytical Hierarchy Process (AHP) (Saaty 1990) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon 1981) was found to be most suitable for the evaluation of HTP. Hence, the developed multi-criteria assessment is performed as follows.

1. Weighting of the assessment criteria using an adapted AHP

According to Saaty (1990), within the framework of the AHP, a decision hierarchy is first created to represent the goals, evaluation criteria, and alternatives. However, this step is omitted in the technology assessment procedure outlined here, since the criteria and the evaluation alternatives have already been defined by steps 1 and 2 of the overall process. Next, the decision criteria are evaluated by pairwise comparisons to derive priorities (in the mathematical sense, weightings), which are subsequently checked for consistency. Finally, the best alternative is selected based on the criteria and priorities. In this procedure, an adapted AHP application is performed because the decision hierarchy (completed by steps 1 and 2) and the final selection of the best alternative (selected in TOPSIS) are neglected. In essence, the AHP is used to derive the criteria weights.

In this work, an expert Delphi survey (cf. Tab. 2.7.) was conducted to prioritise the criteria. These types of surveys are characterised by a systematic multi-step process including feedback loops. The goal is to minimise respondents' misjudgements by giving them the chance to correct or confirm answers and assessments (Rowe and Wright 1999). Due to the high number of potential pair comparisons, the experts were asked to compare criteria according to evaluation categories, as well as to compare the evaluation categories themselves in terms of their relative importance. This approach is common in the AHP due to the hierarchical criterion structure (Peters & Zelewski 2002). Table 2.4. depicts the individual criteria and hierarchy levels evaluated in this work in the context of pair comparisons.

Table 2.4. Assignment of the evaluation criteria in a hierarchical structure according AHP (own composition)

Hierarchy level 1: Dimensions or categories of the criteria (upper criteria)	**Hierarchy level 2: Criteria within the dimensions or categories (sub criteria)**
Economics	Production costs of the final product
	Calorific value of the final product
	Carbon content of the final product
Technological development state and technological efficiency	Technology Readiness Level (TRL)
	Distance of the plant to suitable and available substrates
	Energy balance/ energy efficiency of the process
	Material balance/ material efficiency of the process
Ecological performance	GHG emissions through the process
	Degree of pollution of the process water (with or without treatment depending on the purpose of the assessment)
	Share of recycled phosphorus in the process

Within the hierarchy level, the criteria are now compared, and their importance for the higher level, or at the highest criteria level, the overall evaluation goal (i.e. most efficient treatment of biogenic residues in this case), is estimated. The results of all pairwise comparisons are recorded in an evaluation matrix. At the main diagonal, all values are essentially 1 (corresponds to the same importance), while for a value above (below) the main diagonal in a reflection along the main diagonal, the reciprocal of the original value is obtained (Weber 1993). The following assessment scale developed by Saaty (2000) is used for the pairwise comparisons.

Table 2.5. Evaluation scale for pairwise comparisons within the AHP (Saaty 2000)

Values a_{ij} for pairwise comparisons	**Meaning of the value a_{ij}**
1	Same importance of both criteria
3	Slightly greater importance of one criterion
5	Significantly greater importance of one criterion
7	Much greater importance of one criterion
9	Very much greater importance of one criterion
2, 4, 6, 8	Intermediate values

To determine inconsistencies in the pair comparisons, following Saaty, a Consistency Index (C.I.) and a Consistency Ratio (C.R.) are subsequently determined. With complete consistency of the pair comparisons in the evaluation matrix *A*, there exists a maximum eigenvalue λ_{max} which has the same dimension *n* as the evaluation matrix with the corresponding eigenvector *v* (Saaty 1994). In mathematical terms, this means:

$$C.I. = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$C.R. = \frac{C.I.}{R.I.}, C.R. < 0.1 \text{ to ensure consisteny} \quad (2)$$

R.I. is a random index which is pre-defined through Saaty depending on the number of considered criteria (Saaty 2000).

In this work, AHP software, namely the Excel-based application AHPcalc, was used to determine the criteria weights and consistency values (Goepel 2013). The resulting criteria weighting/prioritisation listed in Table 2.6. for the individual (sub) criteria of HTP was calculated based on the results of the Delphi survey (cf. Table 2.7.). The coloured backgrounds identify the corresponding upper categories (grey: economic efficiency, blue: technological performance, green: ecological performance). The sub-criteria were already prioritised in their entirety on the basis of their overall criteria (weighted arithmetic mean) (cf. Peters & Zelewski 2002). The background calculations can be found in the supporting calculations of Paper VI and can also be requested from the author.

Table 2.6. Weightings of all HTP assessment criteria determined by AHP (own composition)

Assessment criteria	Criteria weighting according to AHP based on Delphi expert survey
Production costs of the final product	28%
Calorific value of the final product	8%
Carbon content of the final product	5%
Technology Readiness Level (TRL)	5%
Distance of the plant to suitable and available substrates	6%
Energy balance/ energy efficiency of the process	11%
Material balance/ material efficiency of the process	4%
GHG emissions through the process	11%
Degree of pollution of the process water (with or without treatment depending on the purpose of the assessment)	9%
Share of recycled phosphorus in the process	13%

2. Application of the weighted criteria in TOPSIS to identify the relative best alternative

Next, the weighted criteria are transferred to TOPSIS. Depending on how many assessment criteria are used, the weightings given in Table 2.6. must be adjusted accordingly in the same ratio, so that 100% always results as a total weight. As an example, reference should be made to Paper VI, in which some criteria were excluded and the weights were hence adjusted. In the exemplary application of the method in Reißmann et al. (2018c), estimated weights were used because at that time the expert-based AHP was not yet completed.

In TOPSIS, the relatively best alternative is sought by constructing the virtual best case and worst case based on the information available, and using these two benchmarks to map the relative merits of the alternatives (Hwang & Yoon 1981). Multi-criteria methods which depict such relative advantages are called multi-attribute decision-making methods with a discrete solution space (Geldermann & Lerche 2014). The advantage of TOPSIS is that it is able to include a large number of criteria even if the preferences are unclear. Thus, no preference information is required by the user, which increases the user-friendliness of the method. Within TOPSIS, the criteria are divided into input (cost) and output (benefit) (see also the classification in Tab. 2.3.). The idea behind this is that high input (output) quantities such as costs (benefits) affect the efficiency of the overall result and thus reduce (increase) it. However, for undesired inputs (outputs), the ratios are reversed, such as for an input of waste (Peters & Zelewski 2007). An assessment of the relative importance of the criteria is not specified in TOPSIS. However, as part of the technology assessment approach presented here, the prioritisation has already been carried out using AHP.

The following procedure is conducted in TOPSIS. A detailed explanation of the individual steps can be found, for example, in Peters and Zelewski 2007.

a. Determination of decision matrix $\underline{D}$: The data of the individual criteria per alternative are entered in a decision matrix $\underline{D}$.

b. Determination of the normalised decision matrix $\underline{R}$: The aim is to normalise all criteria values to the same interval to prevent an unintentional implicit weighting due to economies of scale.

c. Determination of the weighted normalised decision matrix $\underline{V}$: Each column vector of the matrix $\underline{R}$ is multiplied with the corresponding criteria weightings calculated by AHP.

d. Determination of virtual alternatives: From matrix $\underline{V}$, the best and worst criteria are selected to construct a 'positive ideal' A^+ and a 'negative ideal' A^- alternative.

e. Determination of the distances: For each alternative A_i, Euclidean distances (S_i^+; S_i^-) are calculated to the two virtual alternatives.

f. Determination of the efficiency index c_i: This index maps the distances to the best-case and worst-case alternative. The index refers to the real number interval [0, 1] and is higher the closer (farther away) the alternative is to the efficient (inefficient) edge.

In this work, the TOPSIS efficiency index was calculated in Microsoft Excel. The Excel sheets and background calculations are available on request.

Finally, in **step 4** of the assessment procedure, some interesting factors can be varied, and their influence on the overall results can be identified using a sensitivity analysis. As a result, thresholds, break-even points, or development corridors can be derived. To counter uncertainties and to reflect ranges, this is particularly recommended when applying the method in the context of scenarios.

Derivation of key HTP development factors and scenarios

The methodological elements described so far have mainly addressed RQ1 to first analyse the current situation and to use this information to develop the evaluation approach. However, the following elements of the future-oriented analysis of HTP in Germany are dedicated to the target year 2030 and thus address RQ2.

Because the analysis concerns the future, it was first necessary to find information on the probable development of HTP by 2030. Table 2.7. gives a brief overview of the survey methods used to this end.

Table 2.7. Methods used to research the development of HTP in Germany by 2030 (own composition)

Method	Number of participants/ reviewed references	Time	Brief description of content	Paper of origin[1)]	Info. used for paper[1)]	Primary data availability[2)]
Scenario workshop	6 participants	08/18	Based on the initial findings from the reviews, focus group workshop, and first expert survey, an expert scenario workshop was used to develop a 'long list' of important factors of future HTP development, as well as their relationships and interactions. Participants were researchers from the German Biomass Research Centre (DBFZ) working on HTP.	IV	V	Results protocol on request.
Delphi survey	First round: 51 requests, 27 responses Second round: 27 requests, 12 responses	08/18 09/18	Based on the results of the scenario expert workshop, a questionnaire for a Delphi survey was compiled and sent via an online survey. The international participants were asked about HTP developments in Europe and Germany by 2030. They were also asked to conduct pairwise comparisons of the HTP assessment criteria according to the AHP (s. previous section). Besides evaluating with scales, the experts could explain their selection and assessment in text boxes.	IV	V	DDI conform data documentation on request.

[1)] Numbering of papers according to page VI.
[2)] All primary sources are anonymised and thus contain no personal information.
[3)] DDI: Data Documentation Initiative (DDI 2018).

First, a long list of potential development factors for HTP in Germany was compiled based on information concerning the current situation in this regard (cf. Table 2.1.). This information was critically examined and completed with additional factors in a scenario workshop. In addition, an influence analysis was conducted in the workshop to determine how the individual factors affect each other. The instrument used for this was a networking table. With such a table, one determines which influence (no effect, small effect, large effect) one factor exerts on another through direct comparison of the factors. Subsequently, the active and passive effects are cumulated, and the factors are compared using an influence matrix (Kosow & Gaßner 2008).

Initially, these results served as input for the creation of a Fuzzy Logic Cognitive Map (FCM) (Kosko 1986), which was further discussed and partly revised using information from the literature review on HTP. In turn, the information from the FCM and the influence analysis served as input for the preparation of the questionnaire of the Delphi survey. The Delphi survey focused in particular on the following factors concerning the further development of HTP in Germany: probability of occurrence, relevance in case of occurrence, and risk of non-occurrence. The first round of the Delphi survey (n=27) focused primarily on development factors that have a high impact on the overall system according to the FCM indicator 'Centrality' (Obiedat et al. 2011). In the second survey round (n=12), additional factors were added following the feedback from some survey participants.

Using the Fuzzy Delphi Method (FDM) (cf. Saffie et al. 2016), the results of the survey were systematically evaluated. Through the FDM, expert opinions were integrated by means of fuzzy numbers based on a cumulative frequency distribution and corresponding fuzzy integrals. As a result, gaps between the consensus levels of the expert panel were calculated, so a relatively small number of survey participants was sufficient to obtain reliable information on the degree of consensus (Hasan et al. 2017). Hence, two Delphi rounds were enough to reach majority consensus within the expert panel. The result of this process is a list of key development factors of HTP in Germany by 2030, including information on the relevance of their occurrence, probability of occurrence, and risk of non-occurrence. Figure 2.2. provides an overview of the methodological process.

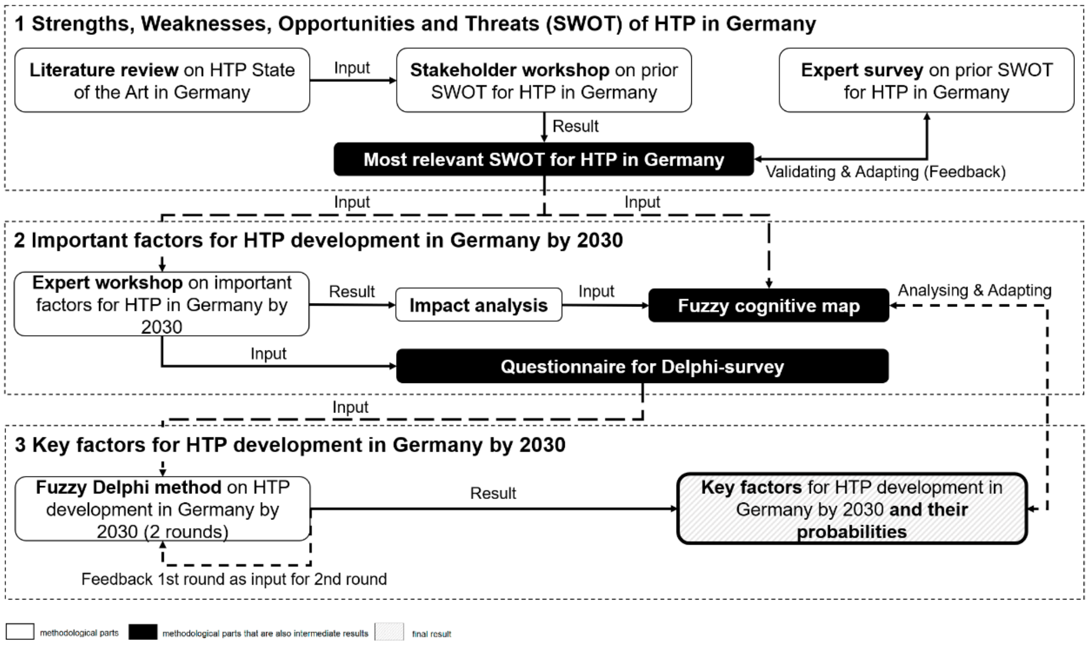

Figure 2.2. Methodological sequence of the derivation of key development factors (own illustration)

Based on the identified key factors, three scenarios for HTP in Germany by 2030 were derived using the following principles:

- Scenario 1 incorporates the factors with the highest probability,
- Scenario 2 incorporates the factors with the highest relevance of occurrence, and
- Scenario 3 considers the highest probability factors but excludes factors with the highest risk in case of non-occurrence.

To test the consistency of the individual scenario factors, a consistency check was executed for each scenario.

Performing the system-level scenario analysis

Based on the key development factors and scenarios derived, a scenario analysis for HTP on the system level was executed. The aim was to analyse the effects of the scenarios on the whole system of key factors by using the FCM. The system describes the totality of key development factors included in the FCM. The scenario factors, which were included but assumed an initial value of ‘0’ (no influence), were changed. To map a strong influence of the corresponding scenario factor, the factor was set to ‘+1’, and a slightly weaker effect was represented at ‘+0.5’. The online software tool ‘Mental Modeler’ (Gray et al. 2013) was used for the system-level scenario analysis.

Plant-level scenario analysis and test application of the assessment tool

Furthermore, the scenarios' effects on a single industrial-scale plant were analysed. As a base case, an industrial-level sewage sludge HTC plant in Germany was assumed, representing the current best available technology (BAT). The plant was characterised as follows.

Table 2.8. Base case study for the multi-dimensional scenario analysis on the plant level (own composition based on data from Blöhse 2017)

Characteristic	Description
Technology type	HTC with a capacity of 14,300 tons of dry matter input per year
Substrate input	Mechanically dewatered municipal sewage sludge
Processing parameters	220 °C, 2 hours residence time, 15 bar, pH-value 7 to 8, no process optimisation
Logistics	20 kilometre distance to the place of substrate occurrence, 40 kilometre distance to the place of usage of the solid product
Product yield/ mass reduction	68% of dry matter input

Based on data from Blöhse (2017), the evaluation criteria for HTP relevant for sewage sludge HTC were first collected for the base case. Considering various assumptions, these values were adjusted for the individual scenarios. The HTC cases were compared with a technology representing the current status quo in sewage sludge disposal. The reference case was thermal drying and subsequent mono-combustion of the dried sludge. The different HTC cases had the same utilisation path: the end product was also fed to a mono-combustion. Using the technology assessment tool, the individual alternative cases were examined for their TOPSIS efficiency and compared with the conventional reference case. To test the plausibility of the instrument, it was assumed that the best scenario also had the best efficiency at the plant level. This hypothesis was checked through the analysis. Subsequently, sensitivity analyses were conducted for influential parameters (i.e. reduction of disposal costs at the sewage sludge incineration plant, different learning rates, different costs and performances of the process water treatment) to determine threshold values compared to the reference case. Thus, the analysis investigated the conditions under which the alternatives were advantageous compared to the reference. As a result, first statements on development goals for the considered metrics could be derived under certain scenario assumptions. However, these statements apply only to the underlying modelled cases, as explained in detail in the discussion section.

Derivation of core recommendations

Finally, the core recommendations were derived on the basis of the key development factors identified as priorities and the information gained from the research (primary and secondary information). A factor identified as being particularly relevant was first checked to see whether it was currently developing positively or negatively. Since a positive development was hypothesised based on the literature and the results of the primary surveys, the derivation process examined how positive development can continue to be ensured, or whether a negative development can be slowed down or even reversed. In addition, based on the model assessment of sewage sludge HTC (s. previous subchapter), some specific recommendations for this case were derived; however, these are not generalisable and require further validation.

For structure, the recommendations have been differentiated between political-legal, technological, economic, ecological, and social areas. Furthermore, suggestions have been made for suitable addressees and possible action horizons to better operationalise the recommendations.

3 Results and discussion

In this chapter, the main results of the work are briefly presented and discussed. Based on this, core recommendations for key stakeholders (i.e. in politics, economics, science, and civil society) in Germany are proposed. More detailed information on individual results and recommendations are part of the attached articles; this chapter only covers key findings. Furthermore, the following is oriented to the intended novel contributions of this work presented at the end of Chapter 1, so that the systematic structure of this work becomes clear. Only the intended contribution (i) is not taken up again here, since this is a methodological result and was already explained in the methods section.

Key development factors for HTP in Germany and scenarios

As mentioned in the methods section, the potentials and barriers for HTP in Germany were first identified on the basis of available literature. Examples of **important potentials** are

- the high energy efficiency of HTP compared to alternative conversion methods,
- the high energy and carbon content of the final products,
- the low substrate procurement costs for biogenic residues and waste,
- the very low, sometimes even negative (as a carbon sink), greenhouse gas potential compared to conventional reference systems, and
- the legal tightening of the Fertilisers Ordinance and Sewage Sludge Ordinance that limit agricultural sewage sludge utilisation, which makes alternative processes such as HTP more necessary, in particular with an integrated phosphorus recovery.

On the other hand, **substantial obstacles** arise, for example, through

- a lack of experience in commercial and industrial continuous operation of plants,
- a lack of knowledge on optimal process calibration, efficient treatment of process water from HTC, and stability of the HTC solid product as a carbon sink in soil,
- legal framework conditions, in particular the legal waste status of HTP products, which makes an energetic usage difficult, and

- missing standards for processes and products (i.e. less transparency for stakeholders).

These findings were further underpinned by information from the first survey and the focus group workshop, and structured using a SWOT analysis. This information base was subsequently used to derive both the technology assessment criteria and the key factors. Table 3.1. provides an overview of the identified strengths, weaknesses, opportunities, and threats, categorised into technological, economic, and ecological aspects.

Table 3.1. Strengths, weaknesses, opportunities, and threats of HTP in Germany (own composition)

	Technological aspects	**Economic aspects**	**Ecological aspects**
Strengths	High energy efficiency High energy and carbon content of end products Suitable for wet biomass	Large product variety	Low GWP
Weaknesses	Knowledge gaps on process basics Less knowledge and experience on efficient process water treatment	No robust data for large-scale business cases Partly low product quality No estimations for product potential	High pollution of HTC process water
Opportunities	Integrated phosphorus recycling Necessity of new sewage sludge treatment options	Inter- and cross-sectional cooperation Estimated decrease in production costs for HTP products	HTC solid product as potential carbon sink
Threats	Suitable substrates are already in other use Variations in feedstock composition and quality Missing reference plants and long-term experiences	Investment uncertainties High competition on sales and procurement markets	Unknown stability of HTC solid product in soil (as carbon sink)

The aforementioned legal potentials and obstacles also continue to be highly relevant. However, these were not included in the SWOT analysis, as no legal technology assessment criteria need to be derived for HTP, and this analysis was primarily used to derive such criteria. Based on this analysis, the Delphi survey, and the scenario workshop, the following key factors presented in Table 3.2. were developed.

Table 3.2. Key development factors of HTP in Germany by 2030 (own composition; including pages 47-49)

x_i	Tagging	Explanation	Relevance of occurrence	Risk in case of non-occurrence	Probability of occurrence
Political-legal factors					
x_1	Regular fuel recognition	HTP energetic products are recognised as standard fuels. This is strongly connected to the third and fourth factor, which represent alternative requirements for the recognition of HTP products as standard fuels.	High	High	Uncertain
x_2	Investment and promotion	Investment incentives (e.g. policy support instruments) and / or technology and research funding programs for HTP are introduced and promoted.	Uncertain	Uncertain	Low
x_3	'End-of-waste' regulation	An end-of-waste regulation is introduced for HTP products (i.e. products from bio-waste, compost, etc.). Comparable regulations already exist for broken glass and steel scrap.	High	Uncertain	Uncertain
x_4	Product certification	Official recognition certificates for HTP products are introduced and issued accordingly by the competent authorities. This helps to reduce uncertainty for practice in terms of classification of HTP products as fuels.	Middle	Uncertain	Low
x_5	Thresholds	Thresholds relevant to HTP (e.g. Federal Pollution Control Act) are relaxed as far as reasonably possible.	Uncertain	Uncertain	Uncertain
x_6	Approval procedures	Approval procedures for new HTP plants are accelerated, which may save costs during the planning and construction phase.	Uncertain	Uncertain	Uncertain
x_7	Product standardisation	The quality of HTP products is standardised (e.g. fuel standard). This helps to reduce uncertainties regarding HTP product and sales markets (e.g. for product users) and enhances transparency.	Middle	High	Low
x_8	Substrate standardisation*	The quality of HTP substrates is standardised (e.g. ISO standard). This helps to reduce uncertainties regarding HTP procurement markets (e.g. for substrate users) and enhances transparency.	Low	-	Low
x_9	Process standardisation	Process standards are introduced (e.g. ISO standards). This helps to reduce uncertainties for plant constructers and operators and enhances transparency.	Low	Uncertain	Uncertain

Economic factors					
x_{10}	Sales markets	The competition on HTP-relevant sales and product markets (e.g. energy carriers, fertilisers, substitutes for chemical products) decreases. Thus, the relative market share for HTP firms may increase.	Low	Middle	Middle
x_{11}	Procurement markets	The competition on HTP-relevant procurement markets (e.g. animal excreta, sewage sludge) decreases. Thus, more usable substrates for HTP may be available, also near the plant location.	Uncertain	Middle	Uncertain
x_{12}	Substrate availability	The available and technically usable amount of substrates increases. Thus, in centralised concepts, plants may handle higher capacities. In decentralised concepts, more substrates are available, also near the plant location, assuming that substrate availability increases equally in Germany.	Low	Middle	High
x_{13}	Disposal costs	Disposal costs for HTP substrates per mass unit (e.g. ton) increase. Thus, revenue for disposing of such substrates may also increase, which would generate additional income for HTP plant operators.	Uncertain	Uncertain	High
x_{14}	Material applications*	HTP products are primarily used for material applications (e.g. as fertiliser, functional carbon). This could result if energy markets remain unprofitable due to legal barriers (missing recognition as regular fuels). Products for HTP may be primarily applied on markets for bio-based products. However, according to expert opinions, this factor strongly depends on missing legal adjustments regarding fuel recognition.	Uncertain	-	Uncertain
x_{15}	Foreign markets**	HTP plant manufacturers and operators concentrate almost exclusively on foreign markets. This may be a result of missing market demand, an insufficient or braking legal framework, low relative market shares for HTP products on related markets, or missing political incentives and willingness to promote HTP in Germany.	Uncertain	Uncertain	Uncertain

Technological factors					
x_{16}	Process water treatment	A cost-efficient and sustainable solution for process water treatment is being developed and applied nationwide. This might promote the overall economic (and ecological) performance of HTP as the polluted process water treatment is currently also a relevant cost (economic) factor which might make HTP concepts uneconomic.	Middle	Uncertain	High
x_{17}	System Integration 1*	HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities. Thus, the location of substrate occurrence and treatment facility could be integrated optimally which leads to lower logistic costs. Also other synergies might be generated, e.g. process water treatment directly by the wastewater treatment plant on site.	High	-	Middle
x_{18}	System Integration 2*	HTP are increasingly being integrated into bio-refineries. This could also generate considerable synergies (e.g. cascade usage networks).	Uncertain	-	Middle
x_{19}	Nutrient recycling*	The nutrient recovery is enhanced. Especially, nutrient recovery from the process water might be promising as the process water must be treated anyway. Due to political and legal frameworks (2017 amendment of sewage sludge ordinance) that especially require phosphorus recovery from sewage sludge, this might be a useful strategy.	High	-	Uncertain
x_{20}	Learning effects	The process understanding and knowledge increases (learning effects, for example through reference systems / business cases). According to learning curve effect theory this will especially reduce costs per produced unit which is why therefore a techno-economic factor (Coenenberg 1999).	High	High	High
x_{21}	Accidents**	Accidents with existing facilities reduce trust in the safety of the technology. This might especially effect plant operator and society which is why this factors is strongly connected to social factors.	Uncertain	Uncertain	Uncertain

Ecological factor					
x_{22}	Life cycle performance*	Research on climate and resource protection by HTP intensifies. Research results also successively improve the life cycle performance due to new insights (e.g. stability of HTC coal in the soil as CO2 sink). This may especially promote social acceptance of the technology. However, the life cycle performance is strongly connected to several other factors (e.g. reduced pollutants in process water after treatment) which is why this factor is just one part of promoting the life cycle performance.	Uncertain	Uncertain	Uncertain
Social factors					
x_{23}	Customer acceptance	Customer acceptance of HTP increases. This may be the result of technological progress, legal adjustments that promote HTP, higher transparency regarding HTP product quality (e.g. end product customers), substrate quality, and process performance (e.g. customers for facilities/plant operators).	Uncertain	Uncertain	Uncertain
x_{24}	Social acceptance	The social acceptance of HTP increases, or society more strongly considers HTP as a resource-efficient technology for future biomass conversion.	Uncertain	Uncertain	Uncertain

<u>Explanation of asterisks:</u>
* According to expert estimations, this factor is not considered a risk if it does not occur. The corresponding field in the table is therefore filled with '-'.
** According to expert estimations, this factor solely represents a risk. Hence, occurrence will have a negative effect.

<u>Additional note:</u>
For the relevance, risks, and probabilities of the factors that are described as 'uncertain', no expert consensus was reached in the Delphi survey.

It should be noted that estimates on the relevance of occurrence, risk in case of non-occurrence, and probability of occurrence are based solely on the Delphi survey experts' assessment. However, 27 European HTP experts participated, which is a relatively large group for this small area of research. The assessments can therefore be considered largely representative, particularly because the panel covers the most important stakeholders (see Paper IV). The Delphi survey participants failed to reach consensus for all factors and categories. Hence, Figure 3.1. simply visualises how the relevance and probability of occurrence of consensus factors in both categories were assessed. The scale represents the results of the fuzzy evaluation (cf. Reißmann et al. 2018d).

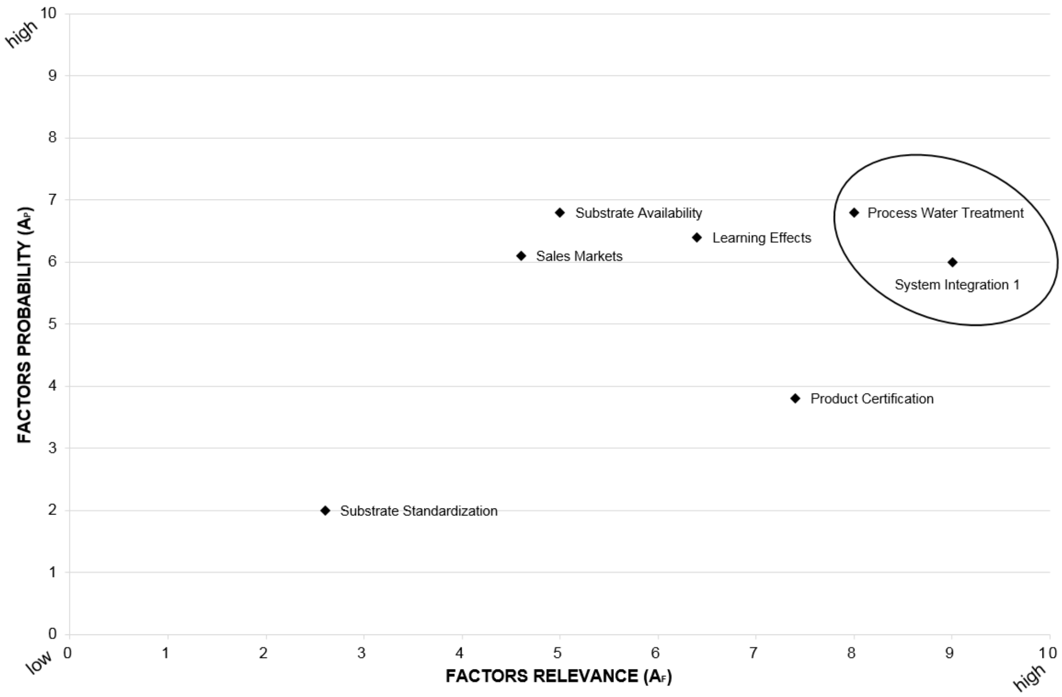

Figure 3.1. Key factor relevance and probability for consensus factors (own illustration)

For the factors on which consensus was reached in terms of both relevance and probability, it can be stated that 'process water treatment' and 'system integration 1' are both highly relevant and likely to occur.

Finally, scenarios based on these key factors were derived, considering only consensus factors. Table 3.3. shows the resulting scenarios and their consistency values. A value close to 3 indicates consistency.

Table 3.3. HTP scenarios for Germany by 2030 (own composition)

HTP scenario	Scenario description
Technological action (TA) $\overline{cons} \approx 3$ Consistent	The available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g. sewage sludge) increase by 2030. Depending on the individual case, high-performance treatment concepts are used for the polluted process water. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed. This means that if the cumulative output quantity is doubled, the production costs are reduced by a factor (learning rate) of a maximum of 30%.
Legal and technological action (LTA) $\overline{cons} \approx 3.3$ Nearly consistent	HTP plants are used decentral and integrated into suitable waste and waste water treatment plants. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed (for explanation, see TA scenario). Products made by HTP with waste and residual materials are legally permitted as standard fuels. Nutrient recycling (e.g. phosphorus) is integrated into HTP.
No action (NA) $\overline{cons} \approx 3.2$ Nearly consistent	The available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g. sewage sludge) increase by 2030. Although the risk in non-occurrence of an efficient process water treatment is rated as uncertain according to the survey results, this factor is excluded, as it is seen as a serious risk based on further discussions with experts. Learning effects are also excluded as their non-occurrence is seen as a serious risk.

System-level scenario analysis

The identified scenarios are now examined regarding their effect on the overall system of factors. This is done using the aforementioned expert assessment based FCM, which has an underlying adjacency matrix that maps the individual influences of the factors on each other. The quantitative representation of the influence belongs to a discrete space containing {-1, -0.5, 0, 0.5, 1}, whereby negative/positive values represent a negative/positive influence, and the value ‘0’ represents no influence. Table 3.4. shows the adjacency matrix.

Table 3.4. Adjacency matrix: FCM factors/concepts relationships (own composition)

x_{ji}	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}
x_1	0	1	1	-1	1	1	1	0	0	-0.5	0	-0.5	-0.5	-0.5	-0.5	1	0	0	0	0	-0.5	0	0.5	1
x_2	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0.5	0.5	0	0.5	0	0	0	0
x_3	1	0	0	-1	1	0.5	0.5	0.5	0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	1	0	0	0	0	0	0.5	0.5	1
x_4	-1	0	-1	0	1	1	1	0	0	0	-0.5	0	-0.5	-0.5	-0.5	0.5	0	0	0	0	0	0	0	1
x_5	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x_6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0.5	0.5	0	0	0	0	0.5	0
x_7	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
x_8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5	0	0	0	0	0	0.5	0.5	0.5
x_9	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	-0.5	0	0.5	0.5
x_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0.5	0	0	0	0.5	0
x_{11}	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0
x_{12}	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0
x_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
x_{14}	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0.5
x_{15}	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
x_{16}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5
x_{17}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0.5	1	0	0	0.5	0.5	0.5
x_{18}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0.5	0	1	0	0	0.5	0.5	0.5
x_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	1	0.5	0.5
x_{20}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	-0.5	0	0	0	0	0	0	0.5	1	0.5
x_{21}	0	0	0	0	0	-0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	-1	-1
x_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5
x_{23}	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
x_{24}	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

This matrix represents the connections between the factors and the influence intensities as well as the direction of the influence (positive, negative). If one transfers these relationships into the FCM, the compounds are additionally deposited with a so-called activation function, which describes the values of the concepts (or factors) in progress – that is, a dynamic component is added to the static representation. In this work, a sigmoid function is assumed as the activation function, as it represents one of the most common functions for FCM applications. Using the activation function, the state of the system changes in the course depending on the scenario's influences (i.e. factor changes). The inference process stops when stability is reached. The final vector state shows the effects of conceptual changes on the whole system of concepts (Leon et al. 2010, Salmeron et al. 2012). Figure 3.2. shows the results and differentiates between a 'high impact' (change +1) and 'lower impact' (change +0.5) case.

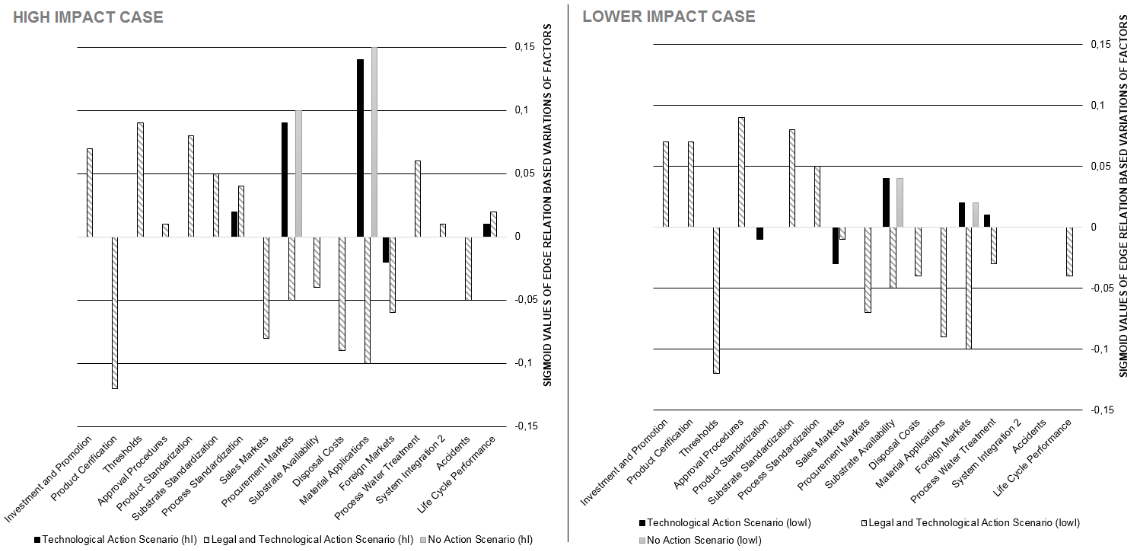

Figure 3.2. FCM system factor variations for HTP scenario with high and lower impact (own illustration)

The main conclusion based on these observations is that, above all, the LTA scenario exerts significant effects on the overall system in both impact cases, which is attributable in particular to the strong influence of the assumed legal framework conditions. The effects are largely positive for the system development. For example, a stronger energy market penetration is foreseeable, which increases the sales potential for the products. In addition, foreign markets become less important, as Germany now also provides sufficient legal certainty for product sales. The dynamics triggered by the LTA scenario also lead to adjustments in the field of approval and planning procedures. Based on the factor descriptions adopted here, for example, approval procedures are accelerated and, if justifiable, simplified to be able to react faster to the stronger market dynamics. Other technological developments are also observed; for instance, the probability of developing a more cost-effective solution for treating HTC process waters increases. In the other two scenarios, the changes are much smaller, which indicates some system stability but also leads to less positive system effects compared to the LTA scenario.

Test application of the assessment tool on plant level scenarios

The scenarios are examined at the plant level in comparison with each other and with respect to a conventional reference system. For this purpose, the developed technology assessment tool is tested for applicability and plausibility. Sewage sludge HTC serves as an exemplary case and the thermal drying of sewage sludge as the reference technology representing the current status quo. Using the assumption-based extrapolation of the individual assessment criteria which are relevant for this case, specific values are obtained for the individual cases, as shown in Table 3.5.

Table 3.5. Criteria values for alternative cases (own composition based on calculation according to data from Blöhse 2017)

Criteria	Unit	HTC-Base	HTC-TA	HTC-LTA	HTC-NA	Reference
Minimising criteria						
Production costs per unit solid product	EUR/t	410.52	401.36	323.39	420.92	329.77
Conversion efficiency/mass balance	%	70	63	63	70	100
Distance of plant to suitable substrates	km	20	20	0.1	20	0.1
Pollution of process water (treated)	mgO_2/l	24340	9787	24340	24340	0
Maximising criteria						
Energy efficiency/energy balance	%	49	80	78	49	18
Share of recycled phosphorus	% P_{in}	0	0	85	0	0

Based on these values, one can already identify which cases are more advantageous than others in certain aspects, but overall advantages are still difficult to assess. In addition, the weightings of the criteria (adjusted proportionally to the criteria considered here according to the original weights in Table 2.6.) are not yet included. If one includes the criteria set and the weightings and transmits this in TOPSIS, the result is as follows.

Table 3.6. TOPSIS efficiency scores for the alternative cases (own calculations)

Cases	TOPSIS efficiency	Rank
HTC-Basis Case	0.14	4
HTC-TA Scenario	0.27	3
HTC-LTA Scenario	0.78	1
HTC-NA Scenario	0.11	5
Reference technology	0.59	2

Table 3.6. shows that the LTA scenario is to be preferred on the basis of the multi-criteria analysis. This result seems plausible, as the LTA scenario performs best on the highly weighted key criteria production costs and recycled phosphorus content. However, the performance in process water treatment is low, which should be considered in making the overall decision. If this particular factor is intolerable for a decision maker, this alternative should not be preferred, and the reference technology should be used instead. However, such basic conditions can already be defined in the criteria system, for example by setting a limit value for the pollution of process water as K.O. criterion, or a higher weighting for this criterion.

Based on this initial case, three parameters are further analysed regarding their sensitivity, since they are expected to have a significant impact on the overall result. The values of the reference technology are kept constant to ensure comparability for all sensitivities. Table 3.7. summarises the results of the sensitivity analysis.

Table 3.7. Main results of the sensitivity analysis for HTC sludge disposal cases (own composition)

Sensitivity	Main results
Reduction in disposal costs for sludge incineration	The reduction in disposal costs was considered for all HTC cases except the LTA scenario, where this was already assumed initially. With a reduction of the costs of up to 50% of the initial case, there is no significant difference in the overall assessment. If the disposal costs for HTC are completely eliminated, the TA scenario and the base case will be more competitive but still less than the reference system. The impact of disposal costs on the overall result can be estimated as medium.
Different learning rates	The learning rates were only varied for the TA and LTA scenarios, as a learning rate was only assumed for these cases. With learning rates below 15% (which corresponds to the initial case), the picture of the overall rating is much more balanced and, in addition, the reference technology is most advantageous. At a learning rate of 25%, the LTA and TA scenarios are both more advantageous than the reference technology. The influence of the learning rate on the overall result can be estimated as very strong.
Costs and performance in process water treatment	This parameter was only varied for the TA scenario, as it is the only one that accepts additional process water treatment to the base case. Even with a high cleaning performance (98%) and low cost increase (50%) compared to the original case, the overall rating hardly changes, and the TA scenario becomes the least favourable case due to the increase in costs. This scenario can only be advantageous compared to all variants if there is a 39% cost reduction compared to the initial case and the highest cleaning performance of 98%. The treatment performance therefore has a small influence on the overall

	assessment if cost increases. Hence, in parallel to an increase in treatment performance, cost reduction potential shall be determined (e.g. energy savings due to the use of waste heat) and used as well. However, the high importance of costs is reasoned in the high weighting of this metric in this work (cf. Table 2.6.), which is why another weighting could provide different results depending on the individual case.

Recommendations

Based on the main results of this work, some core recommendations for different areas and corresponding target groups can be derived. These recommendations mainly refer to the development of HTP in Germany for the treatment of biogenic residues by the target year 2030. In terms of the potential contribution of HTP to the achievement of objectives of the circular economy and bio-economy, the recommendations should indicate the extent to which HTP represents a suitable technology and the extent to which this does not apply. The results of the papers show that HTP can make important contributions to environmental and resource conservation (e.g. phosphorus supply, carbon neutral fuel, bio-based materials), but besides these advantages, various disadvantages and large obstacles can also be seen. For example, techno-economic advantages through the more efficient and thus more cost-effective drying of sewage sludge to the status quo are conceivable. However, process water treatment still incurs costs that are too high and an efficient solution is lacking, which significantly limits the economic benefit of the technology. In the field of sewage sludge utilisation, however, the legal framework conditions under the amended Sewage Sludge Ordinance suggest that HTP could play a role in this area as an alternative conversion technology. Here, however, a political will and the fastest possible implementation are necessary if the first large-scale facilities are to be realised by 2030.

Table 3.8. provides an overview of the main consolidated recommendations based on the results of this work, the primary addressees of the recommendation, and the recommended implementation horizon, which differentiates between short-term (1-2 years), medium-term (> 2-5 years), and long-term (> 5-10 years) (if assessable).

Table 3.8. Key recommendations for HTP development in Germany by 2030 (own composition)

Key recommendations	Horizon for action	Addressees
Recommendations for policy and legislation		
To increase legal certainty in the energetic application of HTP products from residues, a clear legal framework should be sought. In EU law, the EU itself, or in national law, Germany, could specify Art. 6 WFD. Hydrothermally produced biofuels could then be used more easily as a standard fuel, thus opening access to the energy market. According to §5 sec. 1 KrWG in Germany, the prerequisite for this currently already exists. However, legal expertise is required by the companies affected by the standard to classify a situation. To provide more clarity, official product approval notices would be recommended as an alternative to a specific regulation. The legal examination of the waste classification of products from HTP can also be achieved by certification systems. The clearer distinction between products and waste would reduce the risk of litigation (for example, licensing procedures,	Short-term	European and national legislators, competent agencies, standardisation institutes

registration requirements [e.g. REACH regulation]) for HTP companies.		
When using the solid product from HTC as a fertiliser, soil conditioner, or culture substrate, it must also be clarified whether it is waste or a product. Therefore, the above legal recommendations also apply to this area. Furthermore, a license according to § 3 (1) Fertiliser Act is required for use as fertiliser. Currently, however, the solid product from HTC is not included in the corresponding positive list of the Fertilisers Ordinance or approved by the EU Directive. To make this market accessible to the product, an approval is generally recommended, whereby, of course, relevant limit values for pollutants, application rates, etc. must be complied with. However, the legal position for products from sewage sludge must be examined separately, since higher pollutant loads can occur here (especially heavy metals).	Medium-term	European and national legislators, competent agencies
Recommendations for technological development		
Research and development in the field of HTC should focus on cost-effective solutions for the treatment of the liquid phase. There is currently a major techno-economic barrier, and without its timely solution HTC in Germany is expected to have little development opportunities, as this work has shown. A starting point for cost-efficient concepts could be system integration (for example in combination with bio-refineries or waste water treatment plants). Appropriate approaches should be implemented with the involvement of all relevant stakeholders (such as farmers) to make the most of synergies. The advantage of system integrated approaches is cost reduction potential (e.g., short transport routes, waste heat recovery), the integration of efficient nutrient recycling, and cost-effective process water treatment, in combination with other technologies (e.g., biogas plants or waste water treatment plants in terms of process water cycle).	Short-term	Research and development, plant developers, plant operators
HTP can potentially contribute to resource efficiency and the establishment of a circular and a bio-based economy. Therefore, public technology promotion is recommended in the key areas identified here, including in the development of a cost-efficient process water treatment, in system integrated approaches, and to support the construction of the first plants in industrial continuous operation in Germany. In particular, experience in industrial continuous operation is necessary to reduce uncertainties in technical and economic operation. As the learning effect analysis showed, significant cost reductions over time can be achieved, particularly through experience gains. This is essential for a possible competitiveness of HTP in comparison with reference technologies.	Medium-term	Funding agencies, plant developers, plant operators
In Germany, future research and development should focus more on HTL and HTG than on HTC; this could contribute in particular to the mobility and heating sector (e.g. drop-in fuels). Because the burden of by-products in these processes is lower than for HTC, the treatment of these by-products is probably less expensive. Challenges lie in suitable procurement markets. For example, since algae are particularly suitable substrates for HTG, the raw material base in Germany could be insufficient for this purpose. Therefore, research should first focus on HTL- and HTG-suited residual and waste materials that must be disposed of anyway.	Long-term	Research and development
Recommendations for economic operation		

Currently, HTP are not cost competitive with established reference technologies. Taking sewage sludge disposal as an example, it has been shown that thermal recovery as the current status quo is much more cost-effective than HTC in most cases. It is therefore recommended that research and development focus on central cost-efficiency potentials. Without the guarantee of economic operation, HTP will most likely not be established in Germany. All relevant cost groups (production costs, operating costs, investment costs, etc.) should be included. According to this study, cost reduction potentials lie in the field of process water treatment (for HTC), system integrated concepts, and experiences in industrial continuous operation (learning effects). In procurement, the focus should be on a broad residue base, so that decentralised plants (lower transport costs) have sufficiently suitable substrates on site. In the sales area, it is advisable to first focus on material applications (for example, HMF), as the legal framework for energy but also agricultural use is currently inhibiting. An area of business is conceivable for sewage sludge disposal, but the infrastructure of the current incinerators in Germany is not suitable for the solid product from HTC. The sale of by-products such as phosphorus represents an important revenue potential and should be included in potential business models. The actual cost and revenue structure for competitive operation is dependent on the individual case, with the aforementioned cost reduction and revenue potentials representing meaningful approaches in most cases.	Case-dependent	Research and development, plant developers, plant operators
Recommendations for ecological potentials		
The potential environmental benefits of HTP compared to reference technologies (e.g. HTG vs. anaerobic digestion) are currently not fully known. Therefore, for example, the long-term stability of the solid product from HTC in the soil (i.e., carbon sequestration) cannot be accurately estimated, which has increased uncertainty in this area. According to expert statements made in the context of this study, the presentation of the ecological advantages of HTP is a necessary premise for the establishment of this technology in Germany. It is recommended that research focus on essential fields of ecological potential. Based on the present work, CO_2 reduction potentials are especially conceivable if certain substrates are used (e.g. manure, which releases methane if not treated). Resource saving potential is conceivable through integrated nutrient recycling.	Medium-term	Research
Recommendations for societal and customer acceptance		
In public perception, HTP currently plays no role in Germany. The technology is also little known outside the niche in research and development. Hence, potential customers of this technology and products (for example, sewage treatment plant operators) are not very interested in or open to the application of HTP, also because there are still legal, techno-economic, and environmental uncertainties. It is therefore advisable to engage in broader publicity work as soon as the ecological and economic advantages compared to reference technologies have been proven.	Long-term	Not clearly assessable yet

According to the results of this work, the main focus for the future development of HTP in Germany should be in the political-legal and techno-economic fields. First, it can be stated that HTP can contribute to resource and environmental protection and has some potential as an efficient biomass conversion technology (e.g., favourable greenhouse gas balance through high energy efficiency, resource savings through integrated nutrient recycling). However, to date this technology has no promising applications in Germany. Evidence from experts suggests that the initial euphoria surrounding the technology has declined in recent years, first and foremost due to technological barriers in connection with the cost-intensive preparation of the liquid phase from HTC.

In addition, the legal framework for products made from bio-waste and residual materials is also a hindrance for development, as it leads to legal uncertainty among all stakeholders. The willingness of key stakeholders, such as operators of sewage sludge incinerators, to retrofit their infrastructure for disposal of the solid product from HTC is currently rather low, even though the mass reduction of sewage sludge by HTC under certain conditions can be techno-economically advantageous compared to conventional drying processes. Clearly, this potential advantage is currently not enough for HTC to prevail in this area. Alternative markets are to be expected in material applications (e.g. activated carbon) or substitutes (e.g. platform chemicals such as HMF). In contrast, energetic utilisation of the solid product from HTC is currently not expected, since the legal uncertainties have an inhibiting effect. It may be appropriate to focus on other educts that are not waste-based and that can therefore be used both as energy carriers and as fertilisers without any legal obstacles. Based on this analysis, an adaptation of the relevant legal framework enabling a legally certain energetic use of products from waste biomasses (End of Waste Directive) is unlikely, or highly uncertain according to expert feedback.

In contrast, the development of a cost-effective process water treatment technology for HTC in the near future is considered likely, as also indicated by the current research on this subject (cf. Reißmann et al. 2018a). However, the modelled case study showed that process water treatment should be highly cost-effective if HTC is to become competitive in the field of sewage sludge disposal. Even if the results of this study are not generalisable, they show how much the cost structure can outweigh other advantages (in this case, the performance of process water treatment). It is therefore strongly recommended that, in particular, the cost reduction potential for HTP shall be identified and used (e.g. waste heat recovery).

To date, HTL and HTG have only marginally been researched and tested in Germany. Since HTC, especially for sludge utilisation, has lost relevance in recent years due to the problems noted above, it is recommended that the two other technologies be focused on more strongly in the future. The production of liquid and gaseous energy products through HTL and HTG could contribute to the heat and fuel sectors.

Particularly in the fuel sector, potentials are conceivable with regard to the currently intensified ‘Mobilitätswende’ in Germany (e.g. applications in fuel cells).

Important potentials are also recognisable in system integrated solutions. To leverage synergies with other biomass conversion technologies, integrating HTP into bio-refineries or existing infrastructures (such as waste water treatment plants) is a viable option. As a result, for example, the relatively high costs of ‘stand-alone’ solutions can be reduced (cf. Kruse & Dahmen 2018). In addition, system integrated solutions have the advantage that a combined process water treatment is relatively easy to implement (e.g. anaerobic treatment). Nutrient recycling should also be an integral part of such applications, as it may represent a significant advantage of HTP compared to conventional reference systems. Due to the current legal framework (BMU 2017), the recovery of phosphorus is particularly recommended, although other nutrients (such as nitrogen) should also be recovered. The high relevance of nutrient recycling for the development and efficiency of HTP can be seen in the system analysis, in the high weighting of the factor in the context of the AHP, and in the results of the LTA scenario analysis at the plant level.

System integration, cost-effective process water treatment, and nutrient recycling are all closely linked to production costs, investment costs, and potential revenue. As already mentioned, reducing the total cost per unit is essential to compete with alternative and already established technologies. The approaches mentioned above can all contribute to this (e.g. through savings in plant infrastructure due to system integration, or potential sales of recovered nutrients and other by-products). In particular, production costs represent a key metric (e.g. indicated by the high weighting of this metric). Based on the assumption that learning effects will increase in the future, the production costs could be reduced in such a way that competitiveness can be achieved. Paper VI illustrates this with an example case, but further analyses are needed for different cases to derive more meaningful recommendations, possibly also underpinned by quantitative data. The multi-criteria instrument developed in this work can provide a methodological basis for this.

Discussion

This work has identified significant potentials and barriers for the current and future application of HTP for the treatment of biogenic residues in Germany. As part of various methodological elements, primary and secondary information was structured, transparently evaluated, and analysed. The derived key development factors can be regarded as meaningful, since they were collected and validated on the basis of several information bases. In addition, the survey met certain criteria of scientific quality, particularly the representative number of participants in the Delphi survey, the consideration of the entire range of influencing factors mentioned in the literature, and the structured procedure using established methods, such as a SWOT analysis, fuzzy logic, and the scenario technique.

With reference to the aforementioned studies by Suwelack (2016) and Weidner & Elsner (2016), this work provides further insights. The work of Suwelack (2016) has been extended due to the holistic evaluation method specifically for HTP, which was developed through the involvement of various experts within this work. Integral and important components are the weighted evaluation criteria, which were also named by Suwelack (2016) as an explicit research gap. The work of Weidner & Elsner (2016) is expanded by the scenario analysis carried out in this work. In particular, the structured methodology and the inclusion of expertise in addition to secondary literature represent important enhancements that make the results of this forward-looking analysis more robust. In addition to the potentials also mentioned in Weidner & Elsner (2016), this analysis was able to identify important additional factors for future developments of HTP, such as the importance of system-integrative concepts. Therefore, that no other comparable work - besides the two mentioned studies - is known, these findings are to be assessed as novel in this form.

Nevertheless, the analytical results are not generalisable. The analysis of the effects of the HTP scenarios on the overall system exclusively used qualitative information; thus, the quantitative information is not based on objective data, but serves to simplify the interpretation of the system relationships. In addition, the system analysis focused on expert opinions and not on measurements or calculations. It can therefore only be seen as a rough estimate and requires further validation (e.g. through further expert surveys and workshops). Furthermore, the consideration at the plant level is not generalisable and serves primarily to test the technology assessment instrument. Although the results allow conclusions to be drawn on the investigated case, they cannot be used to make any general statements about sewage sludge HTC in Germany. Hence, further work is needed to support these findings (e.g. other case studies and scenarios). To this end, the use of the technology assessment tool, whose functionality was proven here, is encouraged.

4 Conclusion and outlook

Regarding the main research objective of systematically analyse most important potentials and obstacles of HTP development in Germany using a holistic assessment approach, and to provide a series of recommendations to foster these potentials and reduce barriers for future development, this work has provided useful results.

The literature review and primary surveys in this work have shown that HTP has the potential to contribute to the conservation of resources, as the products from HTP can be used for material and energetic purposes and thus can substitute products based on non-renewable resources (e.g. petroleum). Referring to the initial hypotheses, it can be stated that HTP seem to be suitable as technologies for the efficient utilisation of biogenic residues, but above all, political-legal and techno-economic barriers have to be eliminated or solved. In particular, the current framework in waste legislation is a major obstacle to mobilizing the potential of HTP as an energy source, as HTP products are classified as waste rather than as fuel. Accordingly, there is an urgent need for adjustment if products from residual materials that have been treated via HTP should be available for energetic use in future. In addition to this key legal barrier, there is another area of concern in the cost-effective treatment of process water, specifically for HTC. In contrast, potentials that should be exploited are reflected in integrated nutrient recycling and system integrative concepts, which in turn can save costs, which is a key factor in the future success of the technology compared to currently more favorable reference technologies. Hypothesis 1 can therefore be validated in part, as techno-economic and legal barriers have to be overcome, but ecological barriers are currently less relevant.

While the political-legal factors (e.g. regular fuel recognition) mainly relate to the system level, cost and potential savings play an important part in assessing plant-level technologies, especially when it comes to making HTP more competitive with reference technologies. By means of system integrative solutions that optimally contain a nutrient recycling step, costs can be reduced and additional revenue generated; therefore, optimisation potential is assumed. Based on the results of this work, the sole removal of techno-economic barriers, as formulated in hypothesis 2, is not sufficient to enable that the industrial scale application of HTP becomes more likely in Germany, as also political-legal aspects play an important role as already mentioned.

However, techno-economic barriers can indeed probably be evaluated in a more targeted manner by means of the technology assessment instrument compared to less structured assessments (e.g. simple literature reviews), when different application concepts are compared and the corresponding optimisation potential is derived using sensitivity analysis. Thus, this confirms hypothesis 3. The test application to sewage sludge HTC showed when it becomes possible to compete with the reference technology and which HTC concept per se performs best and is to be preferred for the evaluation case. Such information can provide more security to technology developers, users, and investors, and thus help to reduce barriers. Hence, also hypothesis 4 can be validated, at least for this exemplary application case on sewage sludge HTC.

With regard to the future development of HTP in Germany, it can be stated that key factors like learning effects, system-integration, integrated nutrient recycling (especially phosphorus), process water treatment and production costs are of very high relevance, which confirms hypothesis 5. The multi-criteria evaluation of the scenarios showed that only the combination of the best possible development of most of these factors (resp. LTA scenario) enables a promising future for HTP in Germany, which validates the expectation of hypothesis 6. All other factor combinations seem to be hardly successful on system level and for the exemplary plant-level case.

To sum up, the analysis suggests that HTP, as a resource-efficient technology, certainly has potential for the German market and can help support future industrial development in this technology segment for greener production. For the energetic use of the products, the current legal framework must be adapted, i.e. HTP products must lose their waste status. If the German or European legislator does not act here, it is assumed that HTP can only establish itself outside Germany or Europe. Although the material markets for HTP products also represent an interesting sales option, legal obstacles are also evident here (for example, for use as fertilizers). In addition, the currently too high cost of producing HTP products is an obstacle, making it difficult for the technology to prevail compared to reference technologies and penetrate markets. This work has shown this with the example of sewage sludge disposal by means of HTC. In particular, research and technology development are in demand to develop more cost-efficient solutions. This work indicates potential especially in systems-integrative concepts and in nutrient recycling. In addition, cost reductions through learning effects in industrial continuous operation are conceivable. The treatment of process water from HTC is another important point to solve in the future, since the treatment is currently too costly and largely inefficient. Here, also research and technology development are primarily addressed. All the other factors identified in the context of this work should also be considered, with the above-mentioned ones being regarded as essential on the basis of the results of this work and should be prioritized by the mentioned addressees.

Future research

Future research that can be derived from this work can be subdivided into methodological and content-related emphases. Further research activities that are not directly connected to the main issues of this work are presented in Paper I.

Future research with a methodological focus could entail the following:

- The transfer and application of the basic methodological elements of this work (e.g. derivation system for the technology assessment tool [SWOT approach], fuzzy logic analyses for the derivation of scenarios) to other fields of application (e.g. for other emerging technologies).
- The application of the developed technology assessment tool for further analyses, for instance in HTG and HTL case studies.
- The extension of the HTC case study with additional elements, such as additional sensitivities to the reference case, to other reference technologies, to criteria weightings, to other scenarios, or to other product uses (e.g. platform chemicals). This would allow further insights into the potential competitiveness of these technologies compared to reference systems, taking into account different scenarios and applications.
- The examination of more scenario combinations to increase the range of potential future developments. The target year could also be varied, which would require further surveys (for example, expert surveys). The FCM presented here could be varied on the basis of various scenario combinations, so that system effects of other scenarios become visible.
- Due to the ongoing evolution of the subject area, it is recommended that the FCM be updated regularly, in terms of both the essential factors and their connections. For this purpose, further information surveys will initially be necessary. This could also increase the validity of the model.

Apart from this methodological research, further research topics are conceivable, such as:

- The development of cost-effective system integrated solutions for HTP (e.g. integration into a bio-refinery). Such solutions should focus in particular on cost-effective process water treatment and integrated nutrient recycling.
- Solutions that make the most of cost reduction and revenue opportunities to demonstrate techno-economic competitiveness compared to reference technologies.

- A political and legal debate on development opportunities and obstacles. This is urgently needed. To reduce legal uncertainty for affected stakeholders (such as plant operators), advisory services (e.g. guidelines) make sense; research can provide the basis for this. Based on the assumption that there are no legal adjustments in terms of HTP, alternative measures to reduce legal uncertainty are valuable, but must also be widely communicated to the relevant target groups (e.g. regarding the waste status of HTP products in accordance with the Circular Economy Act).
- Increased research on industrial HTP, for example, to better assess business learning effects, economies of scale, and the process behaviour of large-scale plants, and to derive optimisation possibilities. A permanently operated industrial plant should serve as a research base, but this technological maturity has not yet been reached in Germany.
- Research identifying more promising business areas, business strategies, and market potentials (e.g. market analysis, market forecasts, product potential assessments), to enable a technological implementation of HTP at the industry level.
- Participation research involving all relevant stakeholders (from farmer to product recycler). This is recommended to initiate an overarching dialogue, to reduce reservations, and to present the topic more strongly to all target groups (e.g. simulation games, real laboratories).
- Increased research on how to deal with key barriers to reduce uncertainties or to exclude unsuccessful strategies (for example, in the area of infrastructural restrictions due to existing sewage sludge incineration plants, or impediments to the inlet of process water into sewage treatment plants).
- More research on the implementation of HTL and HTG, especially in Germany. In the past there was a focus on HTC, but products from the other two types of process, especially in the fuel sector, could be of increasing relevance in the future.

Further fields for the application of the developed methods

The new approach to technology assessment developed in this work was first tested on the basis of the comparative assessment of future development paths of sewage sludge HTC in industrial continuous operation. It was shown that the proposed assessment leads to plausible results and can help to support decisions for appropriate technology pathways that create uncertainties in various fields of action (e.g. in the techno-economic and legal fields).

First, the technology assessment can also be carried out for HTG and HTL, even though the testing in this work exclusively considered HTC. For this purpose, it is possible to fall back on the already derived criteria: from the long list, small adaptations might be made by selecting the indicators which are necessary for the corresponding evaluation. As both the evaluation method and the corresponding assessment criteria have already been developed through this work, future similar assessments (e.g. for industrial-scale HTG) could be conducted with relatively little effort and would support decision-making for promising future developments. It is also possible to make use of the already derived scenarios or to create new scenarios (e.g. also for other geographical regions than Germany).

Furthermore, the evaluation process can also be used for real practical cases. For example, if an investor is faced with building a large-scale HTC plant in the future and has various design options (e.g. regarding process water treatment), this assessment method, and particularly the derived criteria and their weightings, can help in the decision. This is a central aid for practice, because before this work neither a suitable evaluation method nor appropriate criteria existed.

Furthermore, the methodology presented here is applicable to other emerging technologies characterised by similar uncertainties and development barriers as HTP (e.g. ambiguity about the most appropriate technical options, as in the case of HTC process water treatment). However, the suitability of the criteria developed here cannot be immediately guaranteed. They could be tailored to other technologies by following the criteria derivation approach (step 2 of the technology assessment procedure) and then weighted using AHP (step 3). The other steps of the procedure could be applied unchanged. Nonetheless, the derivation of the criteria is complex and requires various empirical steps; the question is then in which cases it is suitable to apply this extensive procedure. In the case of novel technologies with uncertainties in various fields of action for which no evaluation criteria exist yet, it is recommendable to identify such metrics and apply them to support specific decision-making actions (e.g. for questions on suitable technological options [like process water treatment alternatives in this work] for technology funding).

To enable a broader application of the developed instrument, it could conceivably be transformed into a software tool (e.g. an app). This should be structured in such a way that it leads the user step by step through the evaluation process and is thus as easy to handle as possible, even for users who have no in-depth knowledge of multi-criteria processes. Furthermore, it is essential for this software tool to be designed to be as flexible as possible and to allow, for example, the inclusion of further criteria and the filtering of existing criteria. With an integrated survey module based on the Delphi technique, it would also be possible to adapt the weightings on the basis of the AHP, which would then be automatically implemented by the software, for instance by asking another panel of experts or by adding new criteria. However, from a current perspective, such a transfer into a software instrument only makes sense after the instrument has been validated by means of several case studies and has already been further developed (for example through further expert surveys on the weightings).

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Part II

Appended Articles

Paper I

The following text reassembles the slightly updated full text-version of the article.

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Review

Hydrothermal processes as treatment paths for biogenic residues in Germany: A review of the technology, sustainability and legal aspects

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ABSTRACT

A considerable part of especially wet and sludgy biogenic residues is currently not in material or energetic usage in Germany. Therefore, a key issue for current research is to identify which technologies are most suitable at mobilizing these wet and sludgy materials. Hydrothermal Processes (HTP) appear to be promising treatment options for moist substrates because they require a high water content of 70%–90% for optimal processing. This review provides information on the state of the art and knowledge on HTP, and attempts to determine how suitable these processes are for mobilizing biogenic residues in Germany. We identified technological, economic, environmental and legal potentials and barriers of HTP using a modified content-analysis. About 120 relevant references were identified and analyzed using a structured sampling scheme. The results show considerable advantages of HTP for utilizing wet and sludgy biogenic residues in contrast to comparable biomass treatment processes. Especially, their high process energy-efficiency and low Global Warming Potential from a life cycle perspective. Nevertheless, technological, economic, environmental and legal barriers (e.g. missing data and knowledge on process kinetics; missing legal standards) must be taken into consideration. Finally, research needs are illustrated that must be fulfilled through structured and target-oriented research.

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1. Introduction

Biogenic residues from industrial, commercial and municipal activities are valuable resources. Residues like liquid manure, straw, wood residues from the forestry industry, industrial wood residues, demolition wood, kitchen and garden waste, sewage sludge, and municipal solid waste, can be utilized in a value-enhancing way through appropriate technological applications (Leible et al., 2003; Tröger et al., 2013). The German Government already fosters the material and energetic utilization of biogenic residues by several programs, initiatives and legal regulations aiming to increase the resource efficiency of process chains (BMUB, 2016a). Due to disposal regulations specified through the German Law on Closed Cycle Management and Waste (KrWG, 2012), most industrial residues like plant oils and animal fats as well as municipal waste streams such as food and bio-waste are already being utilized (Brosowski et al., 2016). Regarding the technical potential - describing the part of all physically existing biogenic residues for a certain region and time that is applicable under consideration of availability, environmental barriers (e.g. erosion), technical feasibility, competing uses and legal requirements (Brosowski et al., 2016) - approximately 30% is currently used to produce materials (e.g. compost; fertilizers; cosmetics; pharmaceuticals; bio-plastics) through mainly chemical and physical conversion processes (cf. Thrän and Bezama, 2017; Spiridon et al., 2016; Türk, 2014). A further 27% of the technical potential is energetically used to produce electricity, fuels and heat through thermochemical and biochemical processes (cf. Long and Karp, 2013; Okoro et al., 2017). However, in addition to the substrates that are already tied to material and energetic treatment paths, a technical potential of around 30 million tons of biogenic residues are currently not being used in Germany (Brosowski et al., 2016). Wood residues, cereal straw, animal excreta and sewage sludge are particularly often not in energetic or material use in Germany. Moreover, many biogenic residues used in thermal processes are not suitable because their heating value is under 11 MJ/kg (Brosowski et al., 2016). In addition, some treatment paths for biogenic residues have the potential to increase efficiency through process cascades, i.e. the expansion of existing process chains through material recovery and recycling (Bezama, 2016; Thonemann and Schumann, 2016). With this in mind, the question arises as to whether and how this unused potential can be mobilized, and which processes are most suitable for this purpose.

Hydrothermal processes (HTP) appear to be a promising technology platform for processing wet and sludgy biogenic residues. These technologies use water as their main process medium to convert biomass into materials and fuels at high pressures and temperatures. Because a very moist environment is needed to ensure that the process runs effectively, less energy and thus costs are required in contrast to conventional treatment paths because process steps like substrate thickening and drying are not needed anymore. This makes HTP interesting from an economic and environmental point of view (Schindler, 2015). Thus, HTP seem to be a suitable way to mobilize the wet and sludgy part of the unused biogenic residues in Germany. However, the novelty of the technology platform is associated with uncertainties and barriers for stakeholders (e.g. investment decisions, development of legal standards, funding decisions etc.). Hence, this review aims to contextualize HTP based on technological, economic, environmental and legal criteria.

2. Structure of the review and methods

This review follows the sequence illustrated in Fig. 1. The process is oriented on a modified content-analysis with the aim to provide new insights and enhance the understandability of certain issues through a structured procedure (cf. Moldavska and Welo, 2017).

2.1. Step 1: Preparation phase

First, the review focus was defined according to the study purpose that is to evaluate the extent to which HTP represent a viable option for processing currently unused biogenic residues in Germany. Thus, the central focus was set to identify technological, economic, environmental and legal potentials and barriers of HTP, to derivate corresponding future research needs and to provide information on how to fulfill the research gaps. Based on the review focus, the unit of research was defined as scientific and practical information on the technological, economic, environmental and legal potentials and barriers of Hydrothermal Processes as options for treating biogenic residues in Germany.

Second, a sampling focus including the definition of the time period, type of documents, information sources and document languages must be defined. Because the research on Hydrothermal Processes has gained rising attention since 2000, the period of consideration was set from 2000 to 2017. A large range of different document types was included into the review. Particularly, scientific articles and textbooks, presentations on scientific conferences, conference proceedings, technical reports, legislative texts and websites written in both German and English. The reason for the selection of these document types is that current research on HTP includes much applied-oriented research that is often published via technical reports. Next to this, most recent results are often presented on conferences or websites before they are published in scientific journals or textbooks. Thus, these types of documents should be considered next to scientific articles and textbooks. The information sources used were Google, Google Scholar, Science Direct and Scopus.

Third, to identify documents that are most relevant considering the review focus, we used a sampling scheme (Fig. 2). For every process step of HTP it was determined which information about the aspects under consideration (Technology; Economy; Environment; Legislation) was needed to fulfill the review purpose and thus the defined focus. Based on suggestions of Thrän et al. (2013) the most relevant keywords for each process step and aspect were identified accordingly.

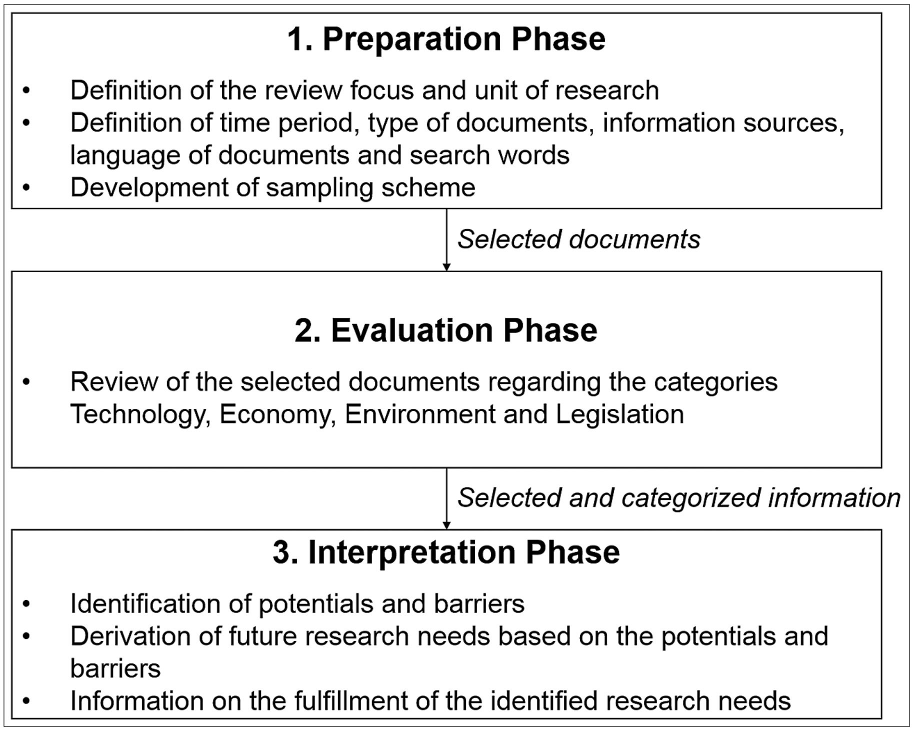


Fig. 1. Sequence of the review (adapted from Moldavska and Welo, 2017).

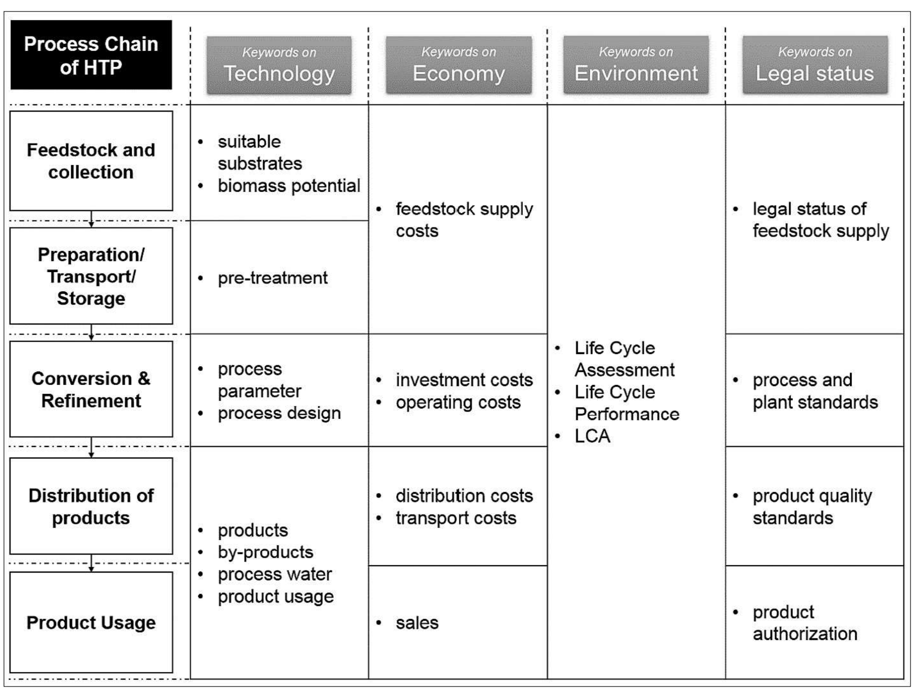


Fig. 2. Sampling scheme to systematically identify the most relevant keywords for document research.

The keywords shown in the boxes of the sampling scheme were used in connection with search words for HTP particularly "Hydrothermal Processes", "Hydrothermal Carbonization", "Hydrothermal Liquefaction" and "Hydrothermal Gasification". The following bullet points clarify the search queries:

- "Hydrothermal Processes AND keyword" (e.g. "Hydrothermal Processes sales"),
- "Hydrothermal Carbonization AND keyword" (e.g. "Hydrothermal Carbonization products"),
- "Hydrothermal Liquefaction AND keyword" (e.g. "Hydrothermal Liquefaction feedstock supply costs"),

- “Hydrothermal Gasification AND keyword” (e.g. “Hydrothermal Gasification by-products”).

The above mentioned search words for HTP were also used without keywords from Fig. 2 to identify more general documents on HTP. To reduce the risk that the search strategy applied could possible exclude relevant documents, an additional test research with more detailed keywords was applied. The words used for this were biogenic residues, municipal waste, sewage sludge and animal excreta. For the test search queries the mentioned words were also connected to the search words for HTP (cf. above mentioned bullet points). In result, the authors claim that the search strategy includes the most relevant documents because also through the test research mostly these documents were identified.

2.2. Step 2: Evaluation phase

Through the keyword research about 120 relevant references were identified and analyzed, whereby not all of them are cited in this article because some information were part of various documents. Every document was carefully reviewed according to the search focus (i.e. the used keyword) and the underlying category (Technology; Economy; Environment; Legislation).

2.3. Step 3: Interpretation phase

Based on the results of the review process, potentials and barriers to HTP for mobilizing the unused technical potential in Germany were identified and interpreted. Finally, future research needs and suggestion to fulfill these needs were derived.

3. Results

3.1. Technological issues of Hydrothermal Processes

3.1.1. Suitable feedstock, feedstock pretreatment and biomass potential for HTP in Germany

The water content is a key parameter for an efficient hydrothermal processing (Greve et al., 2014). An organic dry matter content of less than 30% is generally recommended (Greve et al., 2014; Libra et al., 2011; Ramke et al., 2012). However, the dry matter content of the substrate is the most important parameter for optimizing the desired product output per hour and invested monetary unit because the production rate of the desired output (coal, oil, gas) is proportional to the amount of biomass feed in (Vogel, 2016). Based on this, the suitable organic dry matter content should range between 10% and 30%.

To reach high product mass and energy yields, lignocellulose residues (e.g. corn stalk and dough residues) are very suitable for all HTP types (Kong et al., 2008; Libra et al., 2011; Oliveira et al., 2013; Xiao et al., 2012) whereby algae is the most suitable input for Hydrothermal Liquefaction (HTL – described in section 3.1.2.) (Zhang et al., 2015; Zhu et al., 2013). Generally, no expensive pretreatment is necessary when using the mentioned substrates in HTP. The only exception is that relatively solid substrates (e.g. stalks) must be sufficiently shredded into smaller particles to ensure uninterrupted pumping (Hoffmann, 2014). Based on the mentioned requirements, technical feasibility, structural conditions, ecological issues and social priorities, Brosowski (2015) calculated that Germany has a technical biomass potential for HTP of 16.8 million tons of dry matter. This includes 9.1 million tons of animal excreta, 5.7 million tons of sewage sludge and 2.0 million tons of stalk landscaping materials (Brosowski, 2015).

3.1.2. Parameters and process designs that influence the process

Different types of hydrothermal processes occur depending on pressure, temperature and residence time which is why these reaction parameters are crucial (Greve et al., 2014; Kruse et al., 2013; Peterson et al., 2008). Table 1 shows the typical ranges of these parameters for the main types of HTP: Hydrothermal Carbonization (HTC), Hydrothermal Liquefaction (HTL) and Hydrothermal Gasification (HTG), with its sub-reactions catalytic/low-temperature (subcritical conditions and addition of heterogeneous catalysts) and non-catalytic/high-temperature (super-critical conditions with addition of homogenous catalysts) processes (Elliott, 2008). The parameters are compared to anaerobic digestion as reference biomass conversion process.

Even though much higher temperatures are needed for HTP, the reactions are considerably faster than for the anaerobic digestion process. In addition to process parameters, the catalyst (Guo et al., 2013; Katarzyna et al., 2016; Kong et al., 2008), heating velocity (Katarzyna et al., 2016), solvent (Xiao and Guo, 2006), substrate solid ratio (Dandamudi et al., 2016) and pH value of the feed (Funke, 2012) have a significant impact on the efficiency of the process and the characteristics of the products. Several studies mention a substantial catalytic effect of potassium chloride, citric acid (HTC), alkali carbonate, alkali hydroxide (HTL, HTC) and nickel (HTG) on the processing efficiency (Guo et al., 2013; Klemm et al., 2012; Kong et al., 2008). An optimized calibration of these parameters is recommended in order to ensure a high-quality product (e.g. high calorific value, low pollution level, high nutrient content) and an efficient process. Table 2 lists some calibration examples for temperature, pressure and residence time of specific process designs.

It should be noted that the suggestions mentioned in Table 2 are only valid for the specific process example under consideration and general recommendations have yet to be developed. To get a general impression of the efficiency of typical hydrothermal processes, Table 3 shows process efficiency ranges for HTC, HTL and HTG compared to thermochemical and biochemical biomass conversion processes. Here, process efficiency is based on the yield of the desired product in relation to the total dry matter feed in.

Currently, the most common types of HTP processing systems are batch reactors and continuous-flow operating systems, whereby multi-batch systems are also used (cf. Badoux, 2011). Commonly used reactors are stirring tanks, barrels and tube reactors. Most plants operate as demonstration or pilot plants. The

Table 1
Typical temperatures, pressures and residence times for the main types of HTP (Data from (1) Boukis et al., 2003; (2) Kruse et al., 2013; (3) Peterson et al., 2008; (3) SEAI, 2016; (4) Vogel, 2016).

HTP type	Temperature range	Pressure range	Typical residence time range
HTC – Hydrothermal Carbonization	160–250 °C (2)	10–30 bars (2)	1–72 h (4)
HTL – Hydrothermal Liquefaction	180–400 °C (2)	40–200 bars (3)	10–240 min (1)
HTG – Hydrothermal Gasification			
Catalytic/low-temperature	350-450 °C (4)	230-400 bars (3)	<10 min (4)
Non-catalytic/high-temperature	>500 °C (4)	230-400 bars (3)	<10 min (4)
Reference process: Anaerobic Digestion	32-65 °C (3)	ambient pressure (3)	35-80 days (3)

Table 2
Examples for the optimal calibration of temperature, pressure and residence for HTC, HTL and HTG.

Process example	Temperature (°C)	Pressure (bar)	Residence time (sec)	References
Batch HTC with fermentation residues aimed at high nutrient contents in HTC-char	220	2	14400–28800	Brookman et al., 2016
Batch HTL with waste furniture sawdust aimed at maximum bio-oil yield	280	10	900	Jindal and Jha, 2016
Continuous HTG with glucose in sub- and supercritical water aimed at high product gas yields	>480	340	4	Klingler and Vogler, 2010

Table 3
Process efficiencies of HTP types compared to thermochemical and biochemical biomass conversion processes.

Conversion type	Process	Process efficiency (%)	References
Biomass to coal	Slow pyrolysis (pyrolysis coke)	35	Ronsse et al., 2013
	Torrefaction	75	Ronsse et al., 2013
	HTC	70–90	Klemm et al., 2012
Biomass to liquid	Flash pyrolysis (pyrolysis oil)	65–75	Klemm et al., 2012
	HTL	70–86	Klemm et al., 2012
Biomass to gas	Gasification	54–58	Duret et al., 2005
	Anaerobic digestion	25–71	Weiland, 2010; Yoshida et al., 2003
	HTG	68–85	Klemm et al., 2012

sewage sludge-based HTC process "SlurryCarb" (GlobalWaterAdvisors, 2017) is the most advanced type of HTP so far with the largest plant (located in Rialto, California, U.S.) converting about 180,000 tons of biomass fresh matter into HTC-coal per year (Bolin et al., 2007).

3.1.3. *Products, product use and by-products*

All of the HTP types produce solid, liquid and gaseous outputs whereby there is usually one intended output depending on the type of process used. The desired output of HTC is solid hydro-coal/HTC coal and bio-char. It can be used as a fuel (HTC coal), fertilizer and soil conditioner (bio-char). The liquid bio-crude or HTL oil is the main product of HTL which can be used as a bio-fuel and as a substitute for crude oil in chemical products like cosmetics. HTG mainly produces platform chemicals and bio-fuels based on a mix of hydrogen and methane (HTG product gas) (Kruse et al., 2013). Most HTP products are used for energetic purposes, e.g. as substitutes to lignite, crude oil or natural gas (Vogel, 2016). Thus, the calorific value of the products is crucial. The following illustration shows typical ranges (minimum to maximum) of calorific values of HTC coal and HTL oil compared to conventional fuels. Because there is no robust data for HTG product gases, they are not included in the graph.

Most current applications refine the raw HTL oil afterwards through up-grading processes. This attains a higher quality which is comparable to conventional fuel. For example, HTL oil achieves a calorific value of 46.86 MJ/kg through hybrid processes that combine several up-grading variations (Ramirez et al., 2015). Based on calorific values, HTP products appear to be able to compete with conventional fuels. HTC coal even achieves higher calorific values than raw lignite. In addition to using HTP products for energetic purposes, also other fields of application for HTP products are conceivable. For example, the use of hydro-coal/bio-char as a soil conditioner with integrated carbon sequestration in the soil appears promising (Chan et al., 2007; Glowacki, 2015), but also problems due to adverse effects on plant growth must be considered (Rillig et al., 2010). Using hydro-coal as soil amendment, as much carbon content as possible should be transferred from the feed into the hydro-coal. Generally, this varies between 70% and 75% by weight (water and ash free) which is already a considerably high value. Taking into account that a high carbon content is also an indicator of a high calorific value, these two values of hydro-coal should be maximized (Ramke et al., 2012; Vogel, 2016).

Although a high number of primary carbon is transferred to the hydro-coal, a considerable proportion is split off to the process water. The process water is therefore highly loaded with carbon and other organic compounds (especially nitrogen and phosphate) and – in particular if sewage sludge is utilized - with heavy metals, pathogens and pharmaceuticals that are split off out of the sludge (Ohlert, 2015). Table 4 shows the sum parameters for the organic contamination of HTC process water.

Solutions are currently being sought for the most efficient way to treat the process water. Discharging the process water into a wastewater treatment plant (WWTP) seems to be a simple solution. However, several batch experiments have shown that the COD values are permanently too high for the process water to be simply discharged in the wastewater regarding current legal thresholds. Most WWTP operators do not allow process water to be discharged since thresholds can be exceeded. Due to this, some studies have already investigated pretreating the process water before discharging it. Wet oxidation and membrane processes achieved promising results for reducing pollution and thus the TOC value (up to 74%). That means that after the pretreatment of the process water a discharge into a WWTP will be possible (Loewen, 2013; Ohlert, 2015; Ramke et al., 2012; Reza et al., 2016; vom Eyser et al., 2015; Weiner et al., 2013). Another way to reduce the organic content of the process water is to separate out phosphorus. A positive side effect is that the sequestered phosphorus can be used as a fertilizer. However, such procedures have currently a low feasibility which is why they are not widespread (Remy and Stüber, 2015; Vogel, 2016).

An undesired process water also occurs during HTL although it is usually less polluted than the process water of HTC. After catalytic liquefaction (CatLiq), the TOC of the HTL process water is about 3300 mg C/L which is considerably less critical than the TOC of the

Table 4
TOC, COD and BOD_5 values of process water from HTC (Data from Escala et al., 2013; Ramke, 2011).

Sum parameter	Range of concentration in HTC process water
Total Organic Carbon (TOC)	9000–36,000 mg C/L
Chemical Oxygen Demand (COD)	24,200–68,500 mg O_2/L
Biochemical Oxygen Demand (BOD_5)	10,000–42,000 mg O_2/L

HTC process water. The gaseous phase that occurs during HTL mostly consists of carbon dioxide (~95%) and traces of nitrogen, hydrogen, carbon oxide and methane. Depending on the process design (e.g. hydrofaction, hydrothermal upgrading) 18%–40% of the feed-in dry matter is split off to the gaseous phase. The carbonized organic solid material, which is another by-product of most HTL processes, is often suspended in the HTL oil. Adding alkaline salts can reduce the proportion of this solid phase (Vogel, 2016).

Undesired by-products of HTG include salts and minerals that are part of most feedstock. Most HTG designs do not separate out these materials during the process so that they occur later as an output in the process water. During processing, they often disturb the functionality of the catalyst. Some applications try to separate the salts and minerals during the process, however this is complex because of the phase reactions of the salt-water-organics mix (Müller, 2012; Schubert et al., 2010).

3.2. Economic aspects of Hydrothermal Processes

3.2.1. Feedstock supply costs

HTP feedstock supply costs consist of feedstock prices, logistic costs (collection; transport; storage) and feedstock preparation costs (drying; thickening; crushing; pressing etc.) (U.S. Department of Energy, 2014a,b; Zhu et al., 2013). In terms of the technical biomass potential of HTP in Germany, the feedstock prices of the potential substrates - animal excreta, sewage sludge and stalk landscaping materials - are considerably low because these substrates are residues that must be disposed of in most cases, because of legal requirements like the European Waste Framework Directive (EU, 2008). Studies have estimated average feedstock prices for these substrates. Leuer (2008) calculated an average feedstock price for animal excreta in Germany of between 2.17 and 2.82 EUR/ton of fresh matter. Because sewage sludge must be disposed, WWTP operators are potentially willing to pay for this. HTP is one potential disposal path. Therefore, instead of incurring costs, additional income (disposal costs for plant operators) can be generated by utilizing sewage sludge. However, this is not common practice in Germany so far, which is why a potential revenue - which usually varies between 8.00 and 12.00 EUR/t of fresh matter (Schumacher and Nebocat, 2009) - cannot be calculated. Usually, stalk landscaping materials can be used without cost incurrence because no functioning market for such materials exists in Germany (Menzel, 2015). It should be noted that these numbers are relatively old and further investigations are recommended to generate current data on these prices. Pretreatment and conditioning only seem to be necessary for stalk landscaping material. It is essential to shred the material into small enough particles so that the substrate can be effectively pumped into the plant. Assuming that the preparation costs for landscaping materials used in HTP are similar to those used for biogas production, they range between 4.50 and 5.60 EUR/ton of fresh matter depending on costs for personnel (Leible et al., 2015).

3.2.2. Investment and operating costs

Investment costs (building; equipment; site development) and operating costs (operating material costs; staff costs; maintenance costs; insurance costs) highly depend on the individual business case. Influencing factors can be plant location, composition of the substrates used, scale of the plant, energy and mass balance of the process (especially the proportion of process water related to the product output), process design and calibration of process parameters (AVA CO2 Schweiz AG, 2012; Eberhardt et al., 2011; U.S. Department of Energy, 2014a,b). The process energy balance significantly influences the energy costs - an important part of the operating costs (Buttmann, 2011; Kruse, 2008). Three important aspects must be considered:

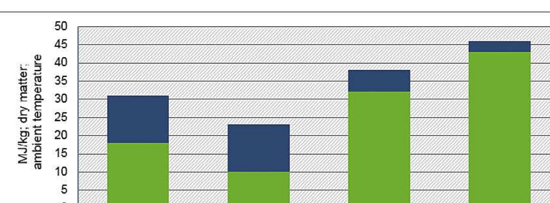
(1) The amount of heated water: To reduce the energy that is necessary to heat the water, using substrates that have a dry matter content of around 20–30% is recommended (Greve et al., 2014).
(2) The loss of energy through dissolved by-products: To reduce this loss, a maximum amount of the process water must be recovered and later used for energetic purposes (for example, when process water was used in biogas plants there was a 19% gain in energy efficiency compared to the reference state) (Greve et al., 2014).
(3) The exothermic process conditions: To increase the overall energy efficiency, a maximum amount of waste heat must be used during the process. Current studies have shown that up to 90% of the required process heat can be supplied through waste heat (Greve et al., 2014; Kruse, 2008; Remy and Stüber, 2015).

Estimating the investment and operating costs for large-scale HTP plants in Germany is difficult because there is a lack of experience with such installations (Vogel, 2016) even that some scenarios for large-scale HTC plant concepts already exist (Child, 2014). Hence, some calculations for these cost components are available. Fig. 4 shows the overall investment costs and annual operating cost calculation for sample case studies compared to conventional reference systems.

In terms of investment costs, large-scale plants have lower costs per ton of dry matter biomass input, which is attributed to economies of scale (Carlino, 1978). No such connection can be drawn for operating costs because they are comparable in both the smallest plant (5000 t/a) and the largest plant (80,000 t/a). Fig. 4 shows that the investment and operating costs of different HTP cases (explained in Table 5) appear to be able to compete with conventional technologies.

3.2.3. Transport and distribution costs

Distribution costs occur when the HTP products are moved to resellers and customers. Cost components may include warehousing costs, transport and logistic costs, or reclamation costs (Springer-Gabler, 2017). The costs are highly dependent on the individual business case and difficult to assess in general. The transport costs have a significant influence on the overall process chain economy. In general, the distance between the location of where the substrate occurs, HTP plant, and the location of the customer is proportional to the increase in transport cost (Eberhardt et al., 2011). The main cost components are staff costs (40–50%), capital costs, energy/fuel costs and costs for maintenance and insurance (10–20% respectively) (Gasafi et al., 2008).



	HTC Coal	Raw Lignite	HTL Oil	Crude Oil
Maximum Calorific Value	31,00	23,00	38,00	46,00
Minimum Calorific Value	18,00	10,00	32,00	43,00

* for crude oil: the heating value is shown because no valid data on the calorific value is avaiable

Fig. 3. Maximum and minimum calorific values of HTC coal and HTL oil compared to raw lignite and crude oil in MJ/kg. (Data from Cerbe et al., 2008; GRENOL GmbH, 2012; Herrmann and Weber, 2011; Ramke et al., 2009; Vogel, 2016).

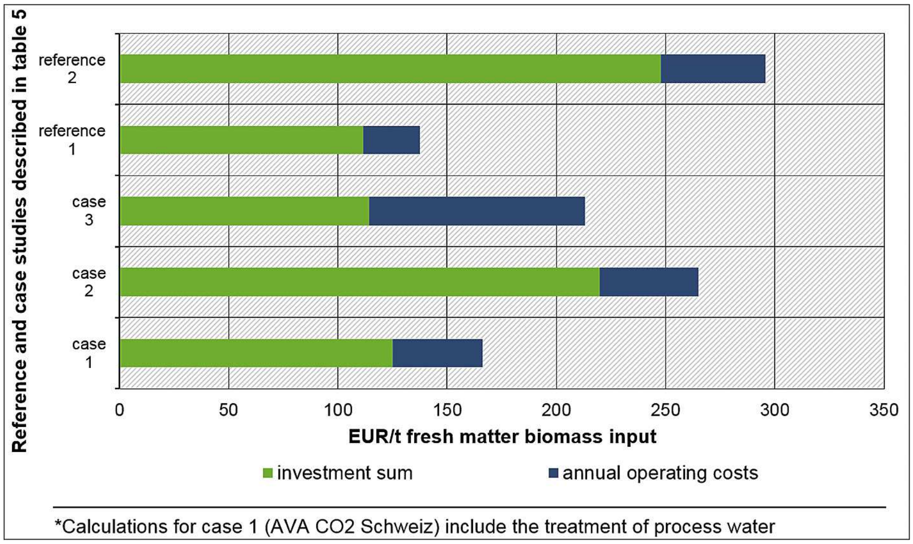


Fig. 4. Investment costs (no annuity) and annual operating costs in EUR per ton of fresh matter biomass input for HTP sample plants compared to conventional reference plants (Data from AVA CO2 Schweiz AG, 2014; Glatzner and Friedrich, 2015; TerraNova energy GmbH, 2011; U.S. Department of Energy, 2016).

Table 5
Case studies representing sample investment and operating costs of HTP plants.

Case study/reference case	Substrates	Plant scale	Reference
Case 1: AVA-CO2 commercial HTC plant	Sewage sludge with 25% dry matter content	80,000 t/a	AVA CO2 Schweiz AG (2014)
Case 2: TerraNova energy pilot HTC plant	Sewage sludge with 20% dry matter content	5000 t/a	TerraNova energy GmbH (2011)
Case 3: Modeled HTL and integrated catalytic hydrothermal gasification (CHG) plant	Sewage sludge with 12% dry matter content	36,500 t/a	U.S. Department of Energy (2016)
Reference 1: Commercial sewage sludge mono-incineration plant	Sewage sludge with 25% dry matter content	30,000 t/a	Glatzner and Friedrich (2015)
Reference 2: Commercial biogas plant	Corn silage with 32% dry matter content	9000 t/a	TerraNova energy GmbH (2011)

Costs for transporting the HTP products (HTL coal, bio-char, HTL oil, HTG gas) to the customer are directly linked to the transport vehicle used (e.g. fuel consumption), the transport distance, the time for loading and unloading, the density of the product (kg/m^3), and the volume of the transport container (m^3) (Eberhardt et al., 2011).

3.2.4. Sales

The sales markets for HTP products are diverse and include energy production, fertilizing and soil conditioning, chemical production, and material applications. Based on the focus of most research projects (Ardissone and Steurer, 2015; Berge, 2015; TerraNova energy GmbH, 2011; Zhengang et al., 2012) and the main products of current installations in practice for all HTP products, the market for energy production seems to be the most promising. The market for soil conditioners is also highly significant for the HTC product bio-char (Glowacki, 2015). Experts estimate also a high potential of HTC products for material applications in future (Titrici et al., 2012)

In energy production, HTP products can be sold to power plants (e.g. fuels) and to industry (e.g. co-incineration). The income from the sale of these products is enhanced by the additional savings that arise from the fact that no emission allowances are necessary for these fuels. However, it must be examined whether energetic HTP products can be utilized within the existing plant and industry infrastructure, or whether reconstruction measures are necessary (Eberhardt et al., 2011). The most important factor for most potential HTP fuel product users is the price (production costs plus profit margin) of the HTP fuel compared to conventional fossil or biogenic fuels. Fig. 5 shows some examples of the production costs of different HTP fuels based on specific plant concepts compared to average fossil fuel production costs (data from Zeymer et al. (2015)) including additional prices for emission allowances and biogenic synthetic natural gas (bio SNG data from Billig (2016)). The production costs are based on all previously described cost components whereby the investment costs are calculated using the equivalent annual cost method (cf. Edge and Irvine, 1981). Table 6 describes the HTP plant concepts.

Currently most energetic HTP products are more expensive in production costs than conventional fossil alternatives. This is due to the novelty of the technology platform and lack of experience with large-scale applications (e.g. absence of learning curve effects). However, it has been noted that production can compete with Bio-SNG. The markets for soil conditioners are also highly relevant to HTC because bio-char can be used for this purpose. The production costs for HTC char lie between 75 and 100 EUR per ton, which is comparable to conventional soil conditioners like peat (Top Agrar Online, 2011).

3.3. Environmental issues of Hydrothermal Processes

The Life Cycle Assessment (LCA) is the most common method used to analyze environmental effects including greenhouse gas emissions (GHG), toxicity, or eutrophication along the entire process chain (see the illustration of the process chain in Fig. 2). Also several LCA have been carried out with respect to HTP (e.g. Ahamed et al., 2016; Benavente et al., 2017). To illustrate this, Fig. 6 shows LCA results for greenhouse gas emissions (GHG) of specific HTP concepts compared to conventional reference systems. Table 7 briefly describes the specific concepts, i.e. HTC using green-waste, HTL using microalgae and HTG using manure as substrate.

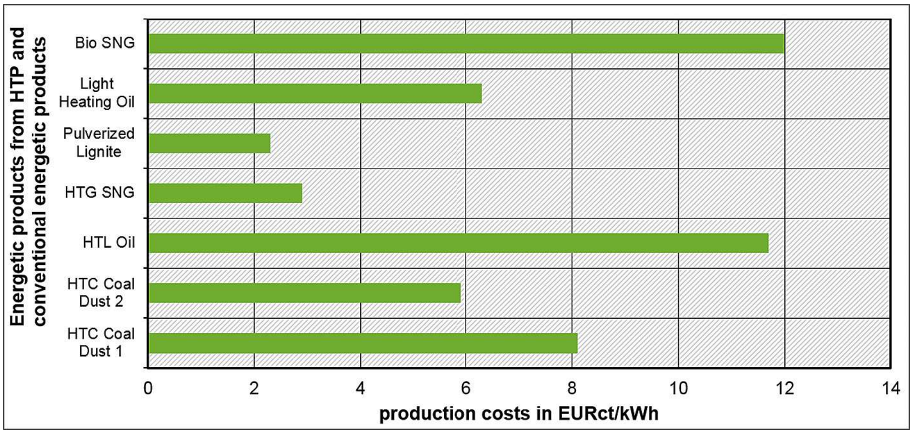


Fig. 5. Production costs in EURct/kWh of sample HTP energetic products compared to conventional fossil and biogenic energy products (Data from Hallesche Wasser und Stadtwirtschaft, 2015; U.S. Department of Energy, 2009; U.S. Department of Energy, 2014a,b).

Table 6
Characteristics of HTP plant concepts as examples for HTP production costs.

Plant concept	HTC 1 (present)	HTC 2 (present)	HTL (modeled)	HTG (modeled)
Substrates	Municipal bio-waste	Fermentation residues	Chlorella algae	Corn stover
Plant scale	2500 t/a	2500 t/a	489,100 t/a	858,480 t/a
Additional product treatment steps	Pelletizing and packaging	Free heat delivery	Including HTL-oil upgrading step	Pretreatment and hydrolysate conditioning of substrate
Product	HTC coal dust	HTC coal dust	HTL oil of fuel quality	Synthetic Natural Gas (SNG)
References	Hallesche Wasser und Stadtwirtschaft (2015)	Hallesche Wasser und Stadtwirtschaft (2015)	U.S. Department of Energy (2014a,b)	U.S. Department of Energy (2009)

The GHG balances of the sample HTL and HTG concepts seem especially promising because they are in fact even negative. In the case of HTL, carbon dioxide binds to algae during the growth phase generating additional GHG credits. In addition, the process water from HTL contains ammonium and phosphate which can be used as a growing medium for algae. This makes mineral growing media superfluous and cuts out additional emissions. Furthermore, the gaseous by-product of HTL (especially hydrogen and methane) is simultaneously combusted to improve the energetics of the system, which saves even more greenhouse gases (Bennion et al., 2015). However, other studies have shown that the installation and use of infrastructure equipment, like HTL upgrading technology, creates a significant energy burden which is very relevant for the overall environmental impact (Ramirez et al., 2015; U.S. Department of Energy, 2014a,b).

In the case of HTG, the high potential for GHG savings is mainly the result of the use of manure, which is a problematic biomass when it comes to greenhouse gas emissions. Manure emits nitrous oxide, which has a global warming potential that is 310 times higher than that of carbon dioxide. Hence, a considerable amount of GHG is saved through the treatment of this biomass as part of the HTG process (Luterbacher et al., 2009).

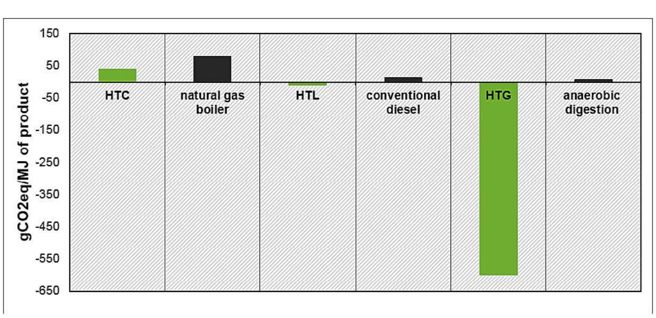


Fig. 6. Carbon dioxide equivalent per mega joule of sample HTP concepts compared to conventional reference systems (Data from Bennion et al., 2015; Hallesche Wasser und Stadtwirtschaft, 2015; Luterbacher et al., 2009).

HTC has a high potential for additional carbon credits by binding carbon to soil using bio-char as a soil conditioner. When indirect effects are also taken into account (e.g. decreased GHG emissions due to a lower production of mineral fertilizers), the overall carbon mitigation potential increases further. According to recent research, the most influential factors for the potential of bio-char to mitigate carbon include the amount of carbon applied with char, additional soil organic carbon, and indirect carbon credits (e.g. the need for fewer mineral fertilizers which is also relevant for other HTP products due to nutrient recovery from process water) (Libra et al., 2011; Luterbacher et al., 2009). However, the long-term stability of hydro-coal in soil has yet to be sufficiently investigated.

When bio-char is added to the soil, CO_2, N_2O and CH_4 soil emissions must be taken into consideration. N_2O emissions are reduced after the application of the char (Lehmann, 2007; Singh et al., 2010; van Zwieten et al., 2010). CO_2 soil emissions are also lower (Lehmann, 2007; Lu et al., 2012; Singh et al., 2010; van Zwieten et al., 2010). In contrast, higher emissions of methane were recorded after bio-char was added to soil (van Zwieten et al., 2009).

In addition to GHG emissions, environmental impact issues, like acidification, human-toxicity, eco-toxicity, and resource depletion or eutrophication, are important if there is to be a holistic assessment of the environmental burden connected with the processes, products and services (Berge et al., 2015; Krebs et al., 2015; Lu et al., 2012). For example, a study of Berge et al. (2015) focusing on food waste HTC (275 °C, 16 h and 32% dry matter content) concluded that hydro-coal combustion has the most beneficial influence on

Table 7
Characteristics of HTP plant concepts as examples for HTP greenhouse gas emissions.

HTP type	Substrate	System scope	Reference system	References
HTC	Green-waste	Green waste from green fields → feedstock supply → HTC processing → pelletizing of HTC coal → transportation and incineration in a 30 kW pellet stove → *heat*	Heat generation through natural gas boiler	Hallesche Wasser und Stadtwirtschaft (2015)
HTL	Microalgae	Algae growth → dewatering → HTL processing → bio-oil stabilization → conversion to renewable diesel (upgrading) → transport and distribution → *mobility*	Conventional diesel	Bennion et al. (2015)
HTG	Manure	Manure preparation and conditioning (ultrafiltration) → HTG processing → production of SNG → *heat and electricity*	Anaerobic digestion	Luterbacher et al. (2009)

the environmental impact (GWP: −99%, acidification: −93% and human-toxicity, non-cancer: −38%) when compared with the use of conventional lignite. In contrast, the process water emissions have the most adverse environmental impact (>60% for human-toxicity, eco-toxicity and freshwater eutrophication). Krebs et al. (2015) evaluated the overall environmental burden of sewage sludge HTC on an industrial scale and show that the process is environmentally promising under specific conditions. These include when waste heat or other local renewables are used in the processing, phosphorus and nitrogen content is reduced in the process water, phosphorus is recovered, HTC coal is used as a substitute for fossil fuels and HTC replaces sewage sludge drying that uses conventional fuels. Most studies generally conclude that HTP has a considerably lower Global Warming Potential (GWP) than comparable conventional fossil and biogenic processes (Berge et al., 2015; Clarens et al., 2013; Krebs et al., 2015; Lehmann, 2007; Ramirez et al., 2015; U.S. Department of Energy, 2014a,b).

3.4. Legal issues surrounding Hydrothermal Processes in Germany

3.4.1. Legal regulations affecting feedstock supply

When examining the suitable HTP feedstock available in Germany (animal excreta, sewage sludge and stalk landscaping materials), the utilization of sewage sludge, in particular, is subject to strict regulations. An amendment to the German Sewage Sludge Ordinance (Klärschlammverordnung (AbfKlärV)) means that the thresholds for agricultural utilization of sewage sludge were tightened, resulting in the loss of a central line of business for many sewage sludge disposal companies. According to this amendment, only sewage sludge from WWTP with a maximum of 50,000 inhabitant-equivalents may be used for agricultural purposes (BMUB, 2016b). In addition, the thresholds of the German Fertilizer Ordinance (Düngemittelverordnung (DüMV)) already impede agricultural usage for some forms of sludge (DüMV, 2012; Greve et al., 2014; Libra et al., 2011). Hence, Germany is currently urgently in need of new, sustainable ways of treating sewage sludge. For instance, co-incineration is not promising for the utilization of sewage sludge because of unavailable capacities of appropriate technical facilities for this purpose in Germany and the release of phosphorous during the incineration process (Glowacki, 2015). Though the new sewage sludge ordinance regulates phosphorous recycling of sewage sludge that exceeds certain phosphorous thresholds, the co-incineration of sludge with high P-values is nevertheless permitted (Greve et al., 2014). Therefore, only a few sewage sludge treatment options remain. Incineration is a suitable energetic treatment option but the energy efficiency is low as a result of an energy-intensive pretreatment process (thickening, drying) of the sludge. With this in mind, HTP seems promising from a legal perspective.

The use of animal excreta through biomass conversion processes has been promoted for several years through regulations like the German Renewable Energy Act (EEG, 2017). Even though the funding schemes of this regulation has been on applied to anaerobic processing, these efforts have shown there is a legal intention to sustainably process animal excreta.

Stalk landscaping materials are defined as bio-waste according to the German Law on Closed Cycle Management and Waste (KrWG § 3 sec. 7 no. 2). This legal scope can be disregarded if the stalk landscaping material consists mostly of logs and huge knots that are used for energetic purposes. However, landscaping material that is suitable for HTP does not fulfil these requirements (Kehres, 2012).

3.4.2. Process and plant standards

Most HTP applications currently operate as pilot or demonstration plants (cf. Boukis et al., 2005; Boukis et al., 2008; Remy et al., 2013). Furthermore, there is a wide range of potential process designs and the optimal calibration of process parameters and other important influencing factors are currently not fully known. This explains why process or plant standards for HTP do not exist so far (Greve et al., 2014). However, they need to be developed in order to reduce uncertainties for technology investors and policy makers (e.g. for funding decision and legal regulations) as well as to enhance the acceptance for the technologies in society.

3.4.3. Product quality standards and product authorization

Standardizing the product quality is highly relevant to increase legal certainty for HTP stakeholders, especially product user, because HTP products become comparable to each other and to other similar products through this. Hence, quality standards governing feedstock, production conditions, product composition and physical, chemical and biological characteristics are already in discussion (Libra et al., 2011). Efforts are already underway to establish quality standards for the use of bio-char as a soil conditioner (e.g. from HTC). The guidelines on the production of bio-char (European Biochar Certificate), which were developed in 2012, define them as materials used for sustainable agriculture produced through pyrolysis with an oxygen content of less than 2% and at temperatures of between 350 and 1000 °C (EBC, 2012). Any bio-char that is not a product or co-product of pyrolysis is regulated as waste in accordance with the European Waste Framework Directive (2008/98/EC). In addition to the European regulations, potential bio-char applications must also be in accordance with national legislation that often defines threshold limits for bio-char based on specific substrates (e.g. sewage sludge). However, the EBC is an initiative and has yet to be officially implemented by European legislation (only Switzerland has officially implemented the EBC). The lack of legislation needs to be clarified before a bio-char market can be implemented (Montanarella and Lugato, 2013). In Germany, the German Fertilizer Ordinance (Article 4 Appendix 2 in connection with Table 7 DüMV) regulates the use of bio-char as a soil conditioner. HTP products are not listed as products according to DüMV, complicating their admittance as soil conditioners. Because no robust data and information regarding the long-term stability of hydro-coal in soils is available, it seems very unlikely that hydro-coal will be allowed to be used as a regular fertilizer in line with

DüMV anytime soon (Greve et al., 2014).

Fuels based on sewage sludge are defined as waste in Germany because of the high level of contamination of the raw material. Thus, they can only be used in waste incineration plants or waste co-incineration plants in accordance with the 17th Federal Emissions Control Act (BImSchV). This is a legal issue because fuels from HTP are also not defined as products according Section 3(1) of the first BImSchV and are legally regarded as waste. Hence, energy-intensive companies have no demand for such fuels because they cannot use them in conventional plants as substitute fuel (Gawel et al., 2015). However, based on Section 5(1) of the German Law on Closed Cycle Management and Waste (KrWG), bio-based fuels from substrates that are not contaminated with pollutants can be used as fuels. Therefore, the legal barriers are highly relevant, especially for fuels based on sewage sludge. European legislation initiatives have already tried to change the legal basis for fuels based on sewage sludge. Recommendations for changing the EU Waste Framework Directive have been put forward including the suggestion of allowing sludge-based fuels that have undergone treatment in a refinement process (2008/98/EC).

4. Discussion

4.1. Potentials and barriers for HTP in Germany

Based on the information of the previous sections, the following key potentials and barriers were identified as shown in Table 8.

4.2. Future research needs

Future research is necessary to solve fundamental problems (highlighted in red in Fig. 7) and to foster the most important potentials (highlighted in green in Fig. 7). Fig. 7 provides an overview of all relevant research areas (according to Fig. 2) and connects them to the current state of knowledge based on the information in the review. Fundamental research is necessary for the research areas categorized in red whereby application-oriented research is recommended for the areas marked green. Further research is recommended for the areas marked amber but they have a lower priority than the other two areas.

Especially, the research gaps that are highlighted in red need a special attention because fundamental research is still necessary for them. To fulfil these gaps, knowledge building is most important. For example, for the treatment of by-products like polluted process water several solution exist as shown in section 3. However, to identify the most optimal solution or combination of solutions it will be necessary to develop theoretically based decision making tools as well as to enable a practical in-field application to verify if the theoretically selected solutions are also operational. Such processes need the involvement of several stakeholders (e.g. technology developers, technology user, product users, retailers, policy makers, researchers) that must share experiences and knowledge.

5. Conclusion

Hydrothermal Processes are an appropriate technology platform for mobilizing currently unused biogenic waste residues in Germany, however several technological, economic, environmental and legal questions have to be considered as Table 8 and Fig. 7 show. HTP are promising regarding their ability to mobilize wet and sludgy biogenic residues that are currently unused and partly subject to disposal pressure (e.g. sewage sludge). Furthermore, HTP products are able to compete with conventional reference products in terms of their calorific value (energy production) and carbon content (fertilizing). Their advantages include being notably more efficient than other technologies that use wet substrates, having the potential to provide an additional biotechnology for existing treatment facilities, and having a lower climate footprint than comparable technologies. However, barriers still exist which could

Table 8
Potentials and barriers for HTP in Germany.

Potentials	Barriers

Technology
• Mobilization of unused wet and sludgy biogenic residues
• Faster processing than other biogenic treatment options
• Process efficiency higher than conventional biogenic treatment options (Table 3)
• Calorific values of energetic HTP products are competitive with conventional fuels (Fig. 3)
• High carbon content in hydro-char
• Parallel phosphorus recycling from process water
• Combination of HTP and wastewater treatment plants (e.g. use of sewage sludge and recovery of process water)
	• Lack of experience with large-scale commercial applications (e.g. learning curve effect)
	• Lack of knowledge regarding:
	  ○ Process kinetics
	  ○ Optimal calibration of process parameters
	• No optimal solution for the treatment of the highly contaminated process water of HTC

Economy
• Low feedstock supply costs (Table 5) due to:
  ○ Low overall substrate costs
  ○ Potential on additional revenues through the use of sewage sludge (disposal costs)
  ○ Low substrate preparation costs
• Competitive investment and operating costs are expected which compare with conventional biogenic treatment options (Fig. 4)
• Production costs of HTC-char expected to compete with conventional soil conditioners
	• Lack of cost data for large-scale commercial plants (due to a lack of experience)
	• Higher productions costs are expected for HTP fuels than for conventional fuels (Fig. 5)

Environment • Significantly lower GWP of HTP possible compared to conventional reference systems • HTC-char as carbon sink in soil	• Little knowledge about stability of HTC-char as a carbon sink in soil • Negative environmental burden of contaminated HTP process water
Legislation • Strict legislation for the utilization of sewage sludge for agriculture enhances need for alternative treatment paths like HTP	• HTP products not authorized as fuel or fertilizers (waste characteristic) • A lack of standards and norms for HTP products and the processing itself increases uncertainties for stakeholders

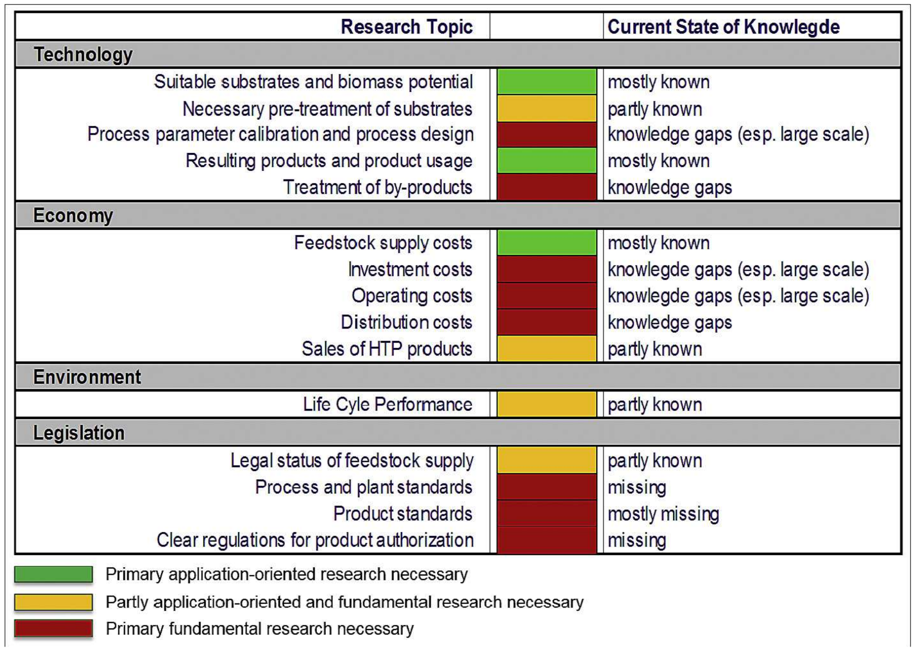


Fig. 7. Future HTP research needs.

impede the successful implementation of HTP in Germany. Fundamental and applied-oriented research is needed to achieve the next level of technological readiness. This includes building upon knowledge of process kinetics and process design, the treatment of by-products, and the cost structure of the entire process chain. Insufficient knowledge about HTC process water treatment leads to high costs (e.g. use of expensive and inefficient treatment options), environmental problems (e.g. process water emissions, contaminant influx) and legal restrictions (e.g. thresholds for wastewater discharge to WWTP). Furthermore, the lack of data on large-scale investments increases the uncertainties for many potentially interested investors, whereby this problem is a result of a general absence of large-scale applications. The categories under scrutiny are intertwined with one another. For example, the lack of knowledge on the long-term stability of hydro-char in soils - mainly an environmental problem - reduces its economic chances due to rising uncertainties on the markets for soil conditioners.

The current legal situation in Germany is both a blessing and a curse. Through the amendment of the German Sewage Sludge Ordinance, new treatment options for sewage sludge are urgently needed. Because sewage sludge is one of the most suitable inputs for HTP this is a general advantage. At the same time, restrictions by BImSchV and DüMV lead to a situation where HTP products from sewage sludge are generally not permitted as regular fuel and soil conditioners.

More research on HTP is necessary to reduce the technological, economic and environmental barriers. A better holistic understanding of this technology platform will help to generate a basis of argument for legal adjustments, will be necessary to enable a successful large-scale application of HTP in biogenic waste management in Germany. Regarding the potential of HTP to utilize sewage sludge, it appears that the current legislation can be adapted in order to simplify the application of HTP for the treatment of sewage sludge. With regard to the current amendment of the Sewage Sludge Ordinance, this could help to put sludge onto an efficient and value-enhancing treatment pathway that meets the new legal requirements.

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Techno-economic and environmental suitability criteria of hydrothermal processes for treating biogenic residues: A SWOT analysis approach

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ABSTRACT

Biogenic residues are valuable resources that could be utilized through appropriate technologies like hydrothermal processes (HTP) that seem to be suitable to transform wet and sludgy biogenic residues into carbon containing materials and fuels. However, this expectation is not sufficiently evaluated so far which is particularly reasoned in missing criteria to assess HTP as options for the management of biogenic residues. In this paper, we present a structured, transferable and transparent approach for developing techno-economic and environmental suitability criteria for currently discussed HTP concepts using methods from strategy development, especially SWOT analysis. For this, a focus group workshop and expert survey with central stakeholder was carried out and enlarged through an extensive scientific literature review to generate a meaningful information basis. The aim is to identify most relevant criteria to assess HTP to each other and to conventional reference systems which reduces uncertainty for future decisions on the suitability of HTP for treating biogenic residues. The results show that especially the Technology Readiness Level (TRL) is of high importance. Next to this, also the production costs, the product potential, the competitive situation on sales markets and the emissions through the process are of high relevance. In following studies, we want to use these criteria for multi-criteria analysis that will be applied on different scenarios for HTP technology development.

1. Introduction

1.1. Background

The efficient use of biogenic resources is an important instrument to support the national and international progress towards sustainable development (BReg, 2016; UN, 2016; UBA, 2016). However, a considerable part of biogenic materials is currently inefficiently used (e.g. energetic usage, despite low heating values) or even not in use, especially because some materials are still considered as waste and not as a resource (cf. Brosowski et al., 2016; Pehlken et al., 2016; Tröger et al., 2013). For example, a recent study calculated a technical potential on unused biogenic residues of 26.9–46.9 million metric tons of dry matter [Mg (DM)] just for Germany. A major share of unused residues is identified for animal excreta (9.1 mill. Mg (DM)), sewage sludge (5.7 mill. Mg (DM)) and landscaping materials (2.0 mill. Mg (DM)) (Brosowski et al., 2015).

In the particular case of sewage sludge, current legal initiatives in most European countries (BReg, 2017; BMEL, 2017; Donatello and Cheeseman, 2013; Stasinakis and Kelessidis, 2012; Werle and Wilk, 2010), as well as logistical and energetic challenges due to its high water content, make the sustainable management of these residual flows an especially challenging task, for which it is important to establish suitable technical alternatives (Werle and Wilk, 2010; Steinle et al., 2009; Zabaniotou and Fytili, 2008).

Exemplary for Germany, the upcoming amendment of the sewage sludge regulation will require an obligatory recycling of phosphorus from the sludges generated in wastewater treatment plants (WWTP). Although this specific obligation depends primarily on the size of the WWTP, most municipal and industrial WWTP will be affected (BReg, 2017). That means, that some sewage sludge treatment possibilities (e.g. direct co-incineration in power plants or with waste) are not suitable anymore, because a phosphorus recovery is not possible with them (cf. Lundin et al., 2004).

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Also the adjustment of Germany's fertilizer ordinance restricts the future usage of sewage sludge. Due to aggravated thresholds for pollutant and nutrient levels regarding sewage sludge that will be used for agricultural purposes, it is expected that this kind of utilization will decrease on 30% of the current level (Klemm and Glowacki, 2015).

In summary, there is currently a large potential of unused biogenic residues already available, and it is expected that new material flows will be available in future, especially because of upcoming legal adjustments and further technical developments in the bioeconomy field (Thrän and Bezama, 2017; Hildebrandt et al., 2017). Hence, suitable technologies for a sustainable management of these materials are needed (Bezama, 2016).

1.2. Hydrothermal process platforms

Hydrothermal processes (HTP) are potentially suitable treatment possibilities for the mentioned biogenic materials (Brosowski et al., 2015), which is also indicated by the increasing scientific (cf. Vogel, 2016; Klemm and Glowacki, 2015; Kruse et al., 2013; Libra et al., 2011) and practical interest (Hallesche Stadt und Wasserwirtschaft, 2015) during the last few years.

HTP aims at converting biomass into gaseous, liquid or solid carbon containing end-products via thermochemical conversion. The procedure needs an aqueous environment for optimal processing, which is why residual materials like sewage sludge and animal excreta are very suitable substrates for applying such technologies (Kruse et al., 2013).

Depending on the process' characteristic parameters (pressure, temperature and residence time) different hydrothermal process types may occur (see Table 1), which can be categorized into three main process types:

(1) **Hydrothermal Carbonization (HTC)** is a coalification process which converts raw biomass into hydro-char, a product that has similar characteristics as fossil coal (Fiori and Lucian, 2017). Hydro-char can be mainly used for energy production (e.g. as fuel or substitute fuel), material applications (e.g. carbon filter) and as fertilizer or soil conditioner in agriculture (Vogel, 2016).
(2) **Hydrothermal Liquefaction (HTL)**, also called hydrous pyrolysis, is a process that converts complex organic structures (such as organic residual streams) into chemicals and crude oil. It mimics the natural geological liquefaction process (Zhang, 2010). The products can be used as liquid fuel for energy production and as substitute to crude oil in the cosmetics sector and chemical industry (Kruse et al., 2013).
(3) **Hydrothermal gasification (HTG)** converts biomass into gas, mainly methane and hydrogen but also other platform chemicals. It mimics the natural gas production process. The products of HTG can be used in the energy sector and chemical industry for different applications (Vogel, 2016; Kruse et al., 2013).

1.3. Goal of this work

Although the suitability of specific HTP concepts for the treatment of biogenic residues such as sewage sludge is currently indeed expected, it has not yet been sufficiently evaluated in a sound scientific manner (cf. HTP Innovationsforum, 2017). Among others, to reduce practical uncertainties (e.g. for investors) and deliver comprehensive and objective information for decision makers (e.g. funding institutions) it will be essential to develop scientifically-based evaluation instruments to compare the suitability of HTP concepts for the treatment of biogenic residues with each other (e.g. HTC vs. HTL) and with reference technologies (e.g. biogas production, pyrolysis). This will be also helpful for assessing future technology developments, e.g. by evaluating different scenarios of HTP development and identify most promising directions from a recent point of view.

An important step is the development of suitable criteria that fit to the evaluation of HTP in the mentioned context. Although many technology assessment criteria exist, there are no criteria that were developed for this specific case of assessment. Recent works on technology assessment concentrates on multi-criteria analysis (e.g. Billig, 2016; Generowicz et al., 2011; Nzila et al., 2012), especially because multiple criteria enables the comparison of technologies under consideration of various dimensions (e.g. technological, economical, ecological and social) which is not possible with such one criterion (Huang et al., 2011).

Mostly, the criteria are taken from guidelines for technology assessment (e.g. VDI, 2000) and selected regarding the purpose of the evaluation. For a structured collection, some guidelines and examples exist that recommend selection factors which can be used (cf. Valenzuela-Venegas et al., 2016; Akadiri and Olomolaiye, 2012; Akadiri et al., 2013). However, the selection of criteria is often executed through the authors of the study without an integration of external estimations. The integration of experts into the criteria development is mostly limited to the step of criteria prioritization. For example, Kamali and Hewage (2017) applied a questionnaire using a 5-point Likert scale to collect professionals' estimations on indicator applicability. Next to such an intuitive prioritization procedure, some studies used the Analytical Hierarchy Process (AHP) to weight criteria through pair-wise comparisons of two criteria carried out by experts (e.g. Bezama et al., 2007; Billig, 2016; Kluczek and Gladysz, 2015).

Although the criteria prioritization or weighting is mostly executed with expert feedback, the initial choice of the criteria set is still very subjective. This is because just a small number of people is involved (mostly just the authors/project team members), which enhances the risk of insufficient selection due to a limited view on the assessment object (e.g. because of professional background). To foster objectivity of such criteria derivation it seems necessary to use a structured approach that integrates also external expert feedback. Although the feedback of one expert is still subjective, the sum of all expert feedback is nearly objective (VDI, 2000).

Hence, the central research aim of this paper is to provide a structured, transferable and transparent approach for the development of dedicated suitability criteria for currently discussed HTP

Table 1
Typical temperatures, pressures and residence times for the main types of HTP [adapted from Kruse et al. (2013); Vogel, 2016; Peterson et al., 2008; Boukis et al., 2003].

HTP platform type	Temperature range (°C)	Pressure range (bar)	Typical residence time range (sec)
HTC	160–250	10–30	60–4320
HTL	180–400	40–200	10–240
HTG - Catalytic/low-temperature	350–450	230–400	<10
HTG - Non-catalytic/high-temperature	>500	230–400	<10

concepts using methods from strategy development including expert feedback. The central method we used is a SWOT (abb. for **S**trengths **W**eaknesses **O**pportunities **T**hreats) analysis, which is an instrument from operations research to develop strategies for organizations (e.g. Kotler et al., 2010). However, SWOT analysis are applied in many different fields today (Helms and Nixon, 2010; Rizzo and Kim, 2005; Valentin, 2001) and this also in a modified and developed way (e.g. Yüksel and Dagdeviren, 2007).

Through the application of the SWOT analysis it is expected to categorize and connect the estimations of experts in this field with information from literature, and to formulate strategic targets for a successful technology application. A considerable advantage of using the SWOT analysis is that potentials as well as barriers are considered for the target and criteria derivation. This increases the holistic nature of the derived criteria, because the risk of a one-sided concentrating on potentials or barriers is minimized. Based on these targets, criteria for the assessment of "target achievement" can be derived. For example, if the target is "increase process energy efficiency" the corresponding criteria for assessing target achievement will be "process energy efficiency".

2. Methodology

The approach applied in this work consisted of a sequence of eight steps (Fig. 1). Although the methodology was developed for the assessment of the suitability of HTP platforms for the management of biogenic residues, the approach can be adopted to other cases of criteria development.

Step 1: Definition of assessment objective and scope.

First, the objective of the assessment must be clearly defined. In this analysis, the objective is to assess the suitability of HTP platforms for the management of biogenic residues. Next to such a basic objective, a clear scope should be determined to set the framework of the analysis. This contains the determination of information on (1) dimensions that shall be addressed: technological, economic, environmental and/or social and (2) spatial scope.

In this paper, the following scope is addressed:

(1) Dimensions: technological, economic and environmental
(2) Spatial scope: Primary Germany, because the expert panel consists mostly of German experts and few experts from Switzerland. However, the literature review also includes international information.

Step 2: Structured collection of information.

Several sources were used for collecting the information necessary for this work. The combination of a literature review and formats that consider expert opinions (e.g. workshops, surveys, personal interviews, telephone interviews) is recommended. Through this, also information that are not published as well as opinions from different stakeholder groups could be integrated. Additionally, the objectivity and transparency of the collected information was very high because many different sources of information were taken into consideration.

To identify relevant experts, we used a top-down stakeholder identification, which will be briefly explained. Stakeholder are groups or individuals that are influenced or have an influence on the possibilities of an organization or company to reach its strategic targets (Freeman, 1984). Reed et al. (2009) recommend a structural approach to identify and classify the most relevant stakeholder

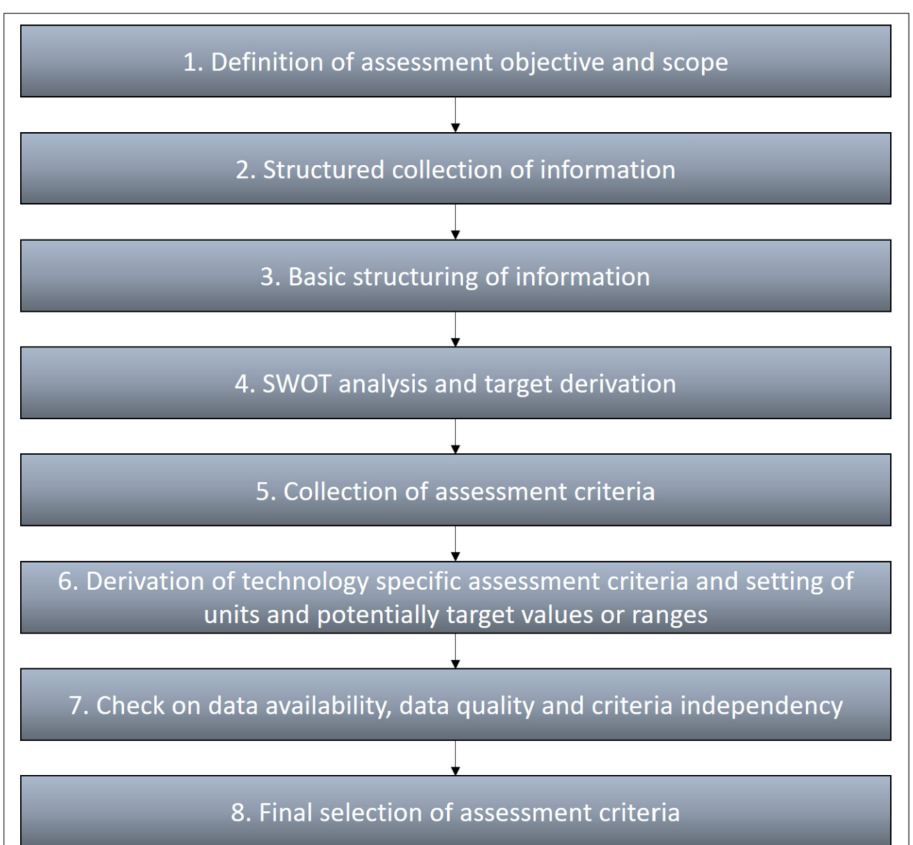

Fig. 1. Methodological sequence of criteria development [own illustration].

consisting of a stakeholder identification, categorization and a final inter-connection of the stakeholder. However, this approach can be modified depending on the objective of the analysis. For this work, we decided to concentrate on the stakeholder identification as we considered it sufficient for this case. A top-down approach was chosen, which means that the stakeholders were identified through an analytical procedure.

Usually, the typical stakeholder of a technology can be identified through the consideration of information-, material-, financial- and energy flows (Fürst et al., 2004). With this in mind, the following information- and material flow chart with corresponding stakeholders was developed based on charts for conceptual environmental analysis of Frischknecht and Schmied (2002).

The boxes in Fig. 2 show the identified stakeholder groups that were considered for the selection of the experts.

As formats for collecting expert opinions, we used a focus group workshop and an expert survey. A total of 41 experts took part in a focus group workshop organized in September 2016 in Leipzig (Germany), through which general information on technological, economic, environmental and legal potentials and barriers of HTP for the management of biogenic residues were collected and discussed. The discussion was open, which means that the experts were asked for general potentials and barriers for every specific dimension as well as other important factors that must be considered without asking for specific details. Additionally, the discussion was introduced with a short presentation illustrating the background. The participants of the focus group workshop were mainly researchers, technology developers and technology user from Germany and Switzerland. To generate a meaningful information basis, it was necessary to include also the other stakeholder. This was carried out through an expert survey. The composition of the survey panel (mostly from Germany) is shown in Table 2. It must be noticed that several participants represent more than one direct stakeholder group which is why the overall survey panel of direct stakeholder includes eight participants. The low participant number is especially due to the novelty of the assessed technology

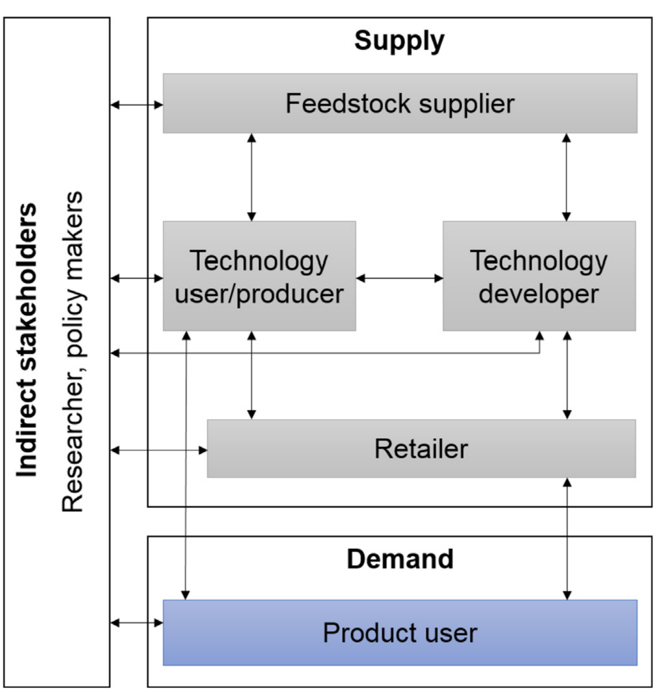

Fig. 2. Material flows and information flows for HTP and corresponding stakeholder [adapted from Frischknecht and Schmied (2002)].

which leads to a low number of experts in field in general.

The expert survey consisted of 13 open formulated questions asking for technological, economic and environmental potentials and barriers of HTP for the treatment of biogenic residues in Germany.

Finally, a review of the available scientific literature (see Reißmann et al., 2018 for more details) was carried out to underpin the results and include also information beyond Germany and Switzerland.

It must be considered that legal assessment criteria will not be developed through this analysis although such information were collected. This is because the criteria derivation will be based on dimensions according to VDI 3780 (VDI, 2000) that focus on technology assessment and do not include legal criteria. However, this information will be considered as frame-setting conditions.

Step 3: Basic structuring of the information.

All these sources of information delivered a comprehensive basis on technological, economic, environmental and frame-setting legal conditions of HTP in the context of treating biogenic residues. To separate the most relevant information is seems necessary to use filtering criteria based on the frequency of mentions. Fig. 3 illustrates the filtering of information in this analysis. The symbol "≥" means "at least mentioned (by/in)".

The 'filtered' information was afterwards categorized in potentials and barriers for every considered dimension. Depending on the objective of the analysis, other filtering criteria can be used. However, the filtering step is essential to differentiate important from less important information why it should not be skipped.

Step 4: SWOT analysis and target derivation.

Through this step, the potentials and barriers were furthermore categorized into strengths, weaknesses, opportunities and threats using a SWOT analysis (cf. Szulecka and Salazar, 2017). Based on the definitions of traditional SWOT analysis (e.g. Rizzo and Kim, 2005; Srivastava et al., 2005), Table 3 shows adapted definitions for strengths, weaknesses, opportunities and threats as well as corresponding key questions which were used in the context of this analysis. The goal of this categorization was to separate internal, which means particular controllable, strengths and weaknesses, from external, which means none controllable, opportunities and threats.

After categorizing the information, the categories were connected through a matrix approach to develop success strategies/targets, on which the assessment criteria were derived. Following strategies/targets are formulated:

- Follow opportunities, which fit to the strengths → *SO-targets*
- Use strengths, to counteract threats → *ST-targets*
- Eliminate weaknesses, to use new opportunities → *WO-targets*
- Develop defenses, to avoid that weaknesses become the aim of threats → *WT-targets*

The derivation of criteria was oriented on their suitability to reach these targets. Hence, the developed assessment criteria refer to advantages (strengths, opportunities) and disadvantages (weaknesses, threats) of the technology.

Step 5 and 6: Collection of assessment criteria, derivation of target specific criteria, setting of target values and categorization between input and output metrics.

Based on the developed targets, criteria for assessing the possibility to reach these targets were derived. For this, established criteria from technology and sustainability assessment were connected to the targets using an arrow/process diagram. Through the usage of established criteria, the connectivity to established methods of technology assessment was guaranteed (cf. Billig, 2016; Kröll, 2007).

Table 2
Characterization of expert survey participants.

Stakeholder	Requested	Responses	Field of operations	Level of operations
Direct Stakeholders				
Feedstock supplier	3	3	Sewage sludge and agricultural residues	National level
Technology Developer	2	2	Biomass Conversion Technologies	National and international level
Technology User	4	4	Hydrothermal carbonization	Regional and federal level
Retailer	3	2	HTC product distribution	National and international level
Product User	4	2	Agriculture and Energy sector	Regional and international level
Indirect Stakeholders				
Policy Maker	1	1	Environmental Policy	Federal and international level
Researcher	5	4	Biomass Research	National and international level
Total	**22**	**18**		
Response Rate	**82%**			

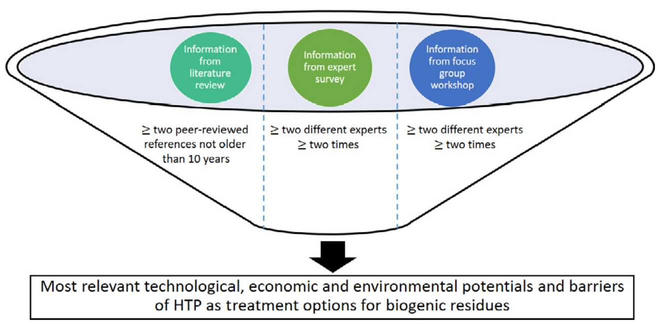

Fig. 3. Filtering criteria for selection of most relevant information [own illustration].

(1) Only those criteria were chosen, that are applicable for at least one target,
(2) The chosen criteria were modified (if needed) with regard to the corresponding target.

Also these selection principles can be modified depending on the assessment objective (as defined in step 1).

The results of the comparative selection was a set of assessment criteria that represent the identified targets. To make these criteria measurable, units must be connected to the criteria. If possible (e.g. because legal thresholds exist), also (minimum/maximum) target values or ranges can be set, e.g. specific efficiency values. Next to this, it was recommendable to further categorize the criteria in input and output metrics. This will be useful, if the criteria should be applied for efficiency evaluation, like Data Envelopment Analysis (Charnes et al., 1978) or Technique for Order Preference by Simularity to Ideal Solution (Hwang and Yoon, 1981). Such methods need a differentiation between input and output criteria.

Table 3
Definitions of SWOT analysis categories oriented on Rizzo and Kim (2005) and Srivastava et al. (2005).

SWOT Categories	Short Description	Key questions
Strengths	Internal resources or capacities which enable HTP platforms and the resulting products a potentially successfully market introduction because there are specific advantages in contrast to potentially competitive technological concepts and the resulting products.	• What are the advantages? • What are the factors supporting the technology?
Weaknesses	Internal limitations, problems or shortages which impede a successfully market introduction of HTP platforms and the associated products in the mentioned systemic contexts, because they lead to serious disadvantages regarding competitive technologies and associated products	• What could be improved? • What should be avoided? • What obstacles hinder progress? • Which elements need strengthening?
Opportunities	Mainly external forces that influence the operating environment of the HTP platforms. These external forces could lead to sudden changes on products or technology markets that go along with new opportunities regarding business segments or procurement and sales.	• What benefits may occur? • What changes in usual practice and available technology may occur? • What changes in Government policy may occur? • What changes in standardization may occur? • What changes in socio-economic behaviour may occur?
Threats	Mainly external caused unfavourable situations that hinder HTP platforms to reach the market because of specific barriers and limitations that occur through that.	• Do the relevant stakeholders show their willingness and interest to support the technology? • What external obstacles do the technology platform face? • Is the changing technological and economic environment threatening the technology platforms market success?

The established criteria were collected for the previous defined dimensions (see step 1). In this case, criteria on technology, economy and environment were selected. We used criteria according to the guideline VDI 3780 (VDI, 2000) and from selected literature on technology and sustainability assessment (Billig, 2016; Buchholz et al., 2009; Markevičius et al., 2010; Shriberg, 2004; Scheffczik, 2003) to create a comprehensive basis. Table 4 shows the used criteria.

For the criteria selection, the following principles were used:

Step 7 and 8: Checking data availability, data quality, independency of criteria and selecting final criteria.

Data availability and a good quality of data are important factors to ensure the usability of the developed criteria for further

Table 4
Selected general criteria for technological and sustainability assessment.

Dimension	Operability	Economy	Environmental quality
Criteria and Sub-Criteria	Technical efficiency • degree of efficiency o energy o material • accuracy • compatibility with other technologies	Cost factors • production costs • life cycle costs • microeconomic values (e.g. ROI) • cost efficiency • external costs	Emissions • pollutants o greenhouse gases o heavy metals • nutrients • noise • rays
	Feasibility • technical know-how • availability of materials/substrates • effort for feedstock supply • type of substrate o residues o other	Profitability • main products o quality • by-products o quality • product diversification • price level • price development • competitive situation	Resource consumption • materials o renewable o non-renewable • land • water
	Usability • robustness • ease of operation • ease of repair	Economic stability • project lifetime • Technology Readi-ness Level (TRL)	Land use change • direct • indirect
	Safety and resilience • resilience against external impacts (e.g. climate events) • resilience against internal impacts (e.g. corrosion)	Employment generation • number of jobs created • quality of jobs created	Contamination (of objects of protection) • soil • water • air • flora • fauna • human

assessments as well as a high quality of assessment results. However, this mostly depends on the specific case of evaluation (e.g. specific process design, cost structure etc.) and cannot be decided beforehand. Next to this, also independency between the criteria must be considered. The value of the results of criteria based assessments increases with rising independency, although an absolute independency of all criteria is hardly reachable. According to Billig (2016), independency can be checked through a calculation of specific default parameter for each criterion of the assessed technology concept. If the impact of difference between the technology concepts superimposes the impact of difference of each criterion they can be regarded as sufficiently independent. However, also this independency check depends on the specific assessment case. Some multi-criteria decision-making concepts do not need such an independency, because they already assume dependency of criteria. The Analytical Network Process (Saaty, 2001) is such a method. Hence, depending on the applied evaluation method the independency check can be perhaps neglected.

An alternative way for a further improvement of the derived assessment criteria set is presented through Cinelli et al. (2016). They recommend proving the criteria set on completeness, reliability and validity based on a criteria ranking through expert estimations and a following correlation analyses which helps to identify parameters of highest interest as well as the connections and dependencies between them.

3. Results

3.1. Essential potentials and barriers of HTP

The described methodology was applied for the development of assessment criteria for the suitability of HTP platforms as treatment options for biogenic residues.

First, the overall information basis (expert survey, focus group workshop and literature review) was filtered through the criteria mentioned in the methods section (step 3) and categorized into technological, economic and environmental potentials and barriers. The results are shown in Tables 5 and 6.

The previous tables show the importance of using expert estimations next to a literature review. In particular, the analysis of the economic aspects is almost completely based on the expert estimations. There was nearly no peer-reviewed literature investigated that is dealing with economic potentials and barriers of HTP.

As previously mentioned, besides these dimensions, also legal aspects are considered as frame-setting conditions. They are especially useful to set threshold for criteria values and make them potentially measurable. For the case of Germany this includes following potentials and barriers.

Legal aspects generating potentials for HTP in Germany:

- Strict legislation for the utilization of sewage sludge for agriculture due to the amendment of the fertilizer ordinance (DüMV) enhances the need for alternative treatment paths like HTP (Libra et al., 2011).
- The new sewage sludge ordinance (AbfKlärV) regulates phosphorous recycling of sewage sludge that exceeds certain phosphorous thresholds, hence the co-incineration of sludge with high P-values is permitted which is a chance for HTP with integrated P-Recycling as treatment option (Greve et al., 2014).

Legal aspects generating barriers for HTP in Germany:

- HTP products from substrates like sewage sludge are currently not authorized as fuel or fertilizers, they are legally seen as waste which impedes the application for some fields. Fuels from sewage sludge can only be used in waste incineration waste co-incineration plants in accordance with the 17th Federal Emissions Control Act (BImSchV) (Gawel et al., 2015).
- A lack of standards (e.g. product certificates) and norms for HTP products and the processing itself increases uncertainties for stakeholders, especially because they are not comparable to competitive products and processes (Libra et al., 2011).

Table 5
Overview of the identified essential potentials of HTP.

Category	Potentials	References
Technology		
Feedstock	Unused wet and sludgy material flows available	Brosowski et al., 2016; Greve et al., 2014
	Very suitable treatment option for sewage sludge	Greve et al., 2014; Libra et al., 2011
Conversion/Processing/Product Composition	High energy efficiency (esp. because no drying and thickening of wet materials is necessary)	Escala et al., 2013; Škerget et al., 2013
	High energy and carbon content of end-products	Roman et al., 2012; Vogel, 2016
	Integrated phosphorus recycling	Heilmann et al., 2014; Dai et al., 2015
Economy		
Costs	Inter- and cross-sectorial cooperation can reduce overall costs	[a]
	Decrease in production costs estimated	Jones et al., 2014; Barreiro et al., 2013
Sales	Large product variety	[a]
Environment		
Environment	HTC-char as potential carbon sink	Libra et al., 2011; Luterbacher et al., 2009
	Global Warming Potential very low compared to conventional reference systems	Bennion et al., 2015; Luterbacher et al., 2009

[a] Denotes a result solely from the discussions in the focus group workshop or from the expert surve

Table 6
Overview of the identified essential barriers for HTP.

Category	Barriers	References
Technology		
Feedstock	Several material flows are already in use	Brosowski et al., 2016; Bardt, 2008
	High variation of feedstock composition and quality	Lin et al., 2017; Li et al., 2016
Conversion/Processing/Product Composition	Missing reference plants and long-term experiences	[a]
	Less knowledge on chemical process basics and process efficiency	[a]
	Missing experiences and knowledge on suitable process water treatment	vom Eyser et al., 2015; Vogel, 2016
Economy		
Costs	Investment uncertainties	[a]
	No financing security for plant construction	[a]
	Missing robust cost data for several business cases (esp. large-scale)	[a]
Sales	No estimations on product potential available	[a]
	High competition on sales market	[a]
	Sometimes low product quality	[a]
Environment		
Environment	High contamination of process water (e.g. COD values to high)	Vogel, 2016; Wirth and Mumme, 2013
	Little knowledge about stability of HTC char in soil as carbon sink	Naisse et al., 2015

[a] Denotes a result solely from the discussions in the focus group workshop or from the expert survey.

Table 7
SWOT analysis for the development of strategic targets on technological aspects.

	Internal Analysis for technological aspects		
External Analysis for technological aspects		**Strengths (S)** (1) High suitability for wet and sludgy residues (2) High energy efficiency of process (3) High energy content and carbon content of end-products	**Weaknesses (W)** (1) Less knowledge on chemical process basics (2) Less experience and knowledge on process water treatment
	Opportunities (O) (1) Integrate phosphorus recycling in process concepts (2) New treatment options for sewage sludge are needed	*SO-targets$_{tech.}$* • Use available wet and sludgy residues, especially sewage sludge (S1/O2) • Improve material and energy balance of the process and integrate P-recycling (S2/S3/O1)	*WO-targets$_{tech.}$* • Focus on knowledge building for (chemical) process design with integrated P-recovery (W1/O1) • Focus on knowledge building on process water treatment, especially with sewage sludge as feedstock (W2/O2)
	Threats (T) (1) Several material flows already in use which reduces available feedstock (2) Variation of feedstock composition and quality (3) Missing reference plants and long-term experiences	*ST-targets$_{tech.}$* • Concentrate on available and best suitable wet and sludgy feedstock (S1/T1/T2)	*WT-targets$_{tech.}$* • Focus on knowledge building on (chemical) process design and process water treatment for existing plants (W1/W2/O3)

- Current legal thresholds on the discharge of waste water into public waste water treatment plants aggravates the necessity of suitable solutions for process water treatment (optimally on-site) (Reißmann et al., 2018).

3.2. SWOT analysis and development of strategic targets

Through a SWOT analysis, factors were identified that are unfavourable or favorable for a successful application of HTP as

Table 8
SWOT analysis for the development of strategic targets on economic aspects.

	Internal Analysis for economic aspects		
External Analysis for economic aspects		**Strengths (S)** (1) Large product variety	**Weaknesses (W)** (1) No robust data for large-scale business and reference cases (2) Sometimes low product quality (3) No estimations for product potential
	Opportunities (O) (1) Inter- and cross-sectorial cooperation (2) Estimated decrease in production costs for HTP	*SO-targets$_{econ.}$* • Focus on products with highest estimated decrease in production costs (S1/O2)	*WO-targets$_{econ.}$* • Use cooperation to generate and share data for business cases (W1/O1) • Focus on products with high quality and high estimated decrease in production costs (W2/O2) • Estimate product potential and integrate estimated decrease in production costs (W3/O2)
	Threats (T) (1) Investment uncertainties and missing financial security (2) High competitive situation	*ST-targets$_{econ.}$* • Focus on product markets with relative low competitive situation (e.g. find niche) (S1/T2)	*WT-targets$_{econ.}$* • Estimate product potential and generate data for business cases to reduce investment uncertainties (W1/W3/T2)

Table 9
SWOT analysis for the development of strategic targets on environmental aspects.

	Internal Analysis for environmental aspects		
External Analysis for ecological aspects		**Strengths (S)** (1) Low Global Warming Potential (GWP)	**Weaknesses (W)** (1) High contaminated process water
	Opportunities (O) (1) HTC char as carbon sink	*SO-targets$_{env.}$* • Focus on the potential of GWP (CO_2) reduction via HT processes and products (S1/O1)	*WO-targets$_{env.}$* • Ensure a high carbon transfer into the end-product to reduce process water contamination and foster quality of end-product (W1/O1)
	Threats (T) (1) Unknown stability of HTC char in soil	*ST-targets$_{env.}$* • Concentrate on greenhouse gas reduction potential through processing (S1/T1)	*WT-targets$_{env.}$* • Focus on the suitable and ecological treatment of by-products and avoid negative environmental effects due to knowledge gaps (W1/T1)

options for the treatment of biogenic residues. Based on this, success strategies/targets can be derived which furthermore were used to develop assessment criteria. Tables 7–9 show the results of the SWOT analysis.

The SWOT analysis for technological aspects shows that strategic targets regarding the availability of the substrates, process water treatment and suitable process design are most important. Especially knowledge building seems essential to improve the potential success of HTP concepts for the management of biogenic residues. Some of the targets could be underpinned with quantitative values if available (see Section 3.3). For example, the target S1/O2 can be quantified through moisture content of the substrate (parameter for "wet and sludgy") or maximum distance to the treatment plant (parameter for "availability").

Economic targets concentrate on production costs, product potential and product quality as well as data availability for business cases. Some of these targets seem to be easy to connect with a criterion, e.g. production costs which is already an economic assessment criterion. Other criteria seem to be more complicated to asses, such as data availability on business cases. Usually, such aspects will not be addressed through economic evaluation criteria. Through the applied method also these kinds of issues will be connected to criteria which shows the added value of this structured approach. Also for the economic targets, some of the corresponding criteria should be quantifiable, e.g. production costs.

Environmental targets refer especially to the GWP of HTP and resulting products as well as the environmentally friendly treatment of by-products like the contaminated process water. Especially the development of criteria for the environmentally friendly process water treatment will be new and innovative because most reference processes to HTP (e.g. pyrolysis) are not confronted with such contaminated liquid by-products. Hence, no criteria can be

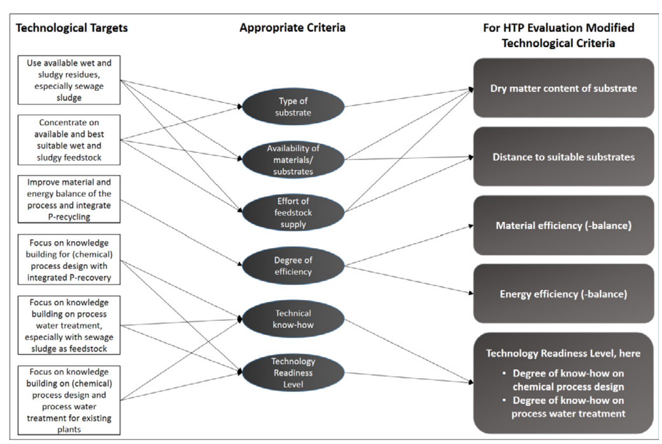

Fig. 4. Process diagram for the derivation of technological criteria.

easily adopted from comparable technology assessments.

3.3. Development of assessment criteria

Based on Table 4 and the explanations made for steps 5 and 6 of the methodology section, the general criteria were connected to the SWOT targets. The chosen general criteria were modified to fit the HTP targets. Generally, sub-criteria were preferred because they are more specific than main criteria. Just for the case that the target fits to several sub-criteria of a main criterion the main criterion was chosen. Figs. 4–6 show the arrow/process diagrams for the connection of strategic targets and criteria as well as the derived modified criteria for the HTP evaluation.

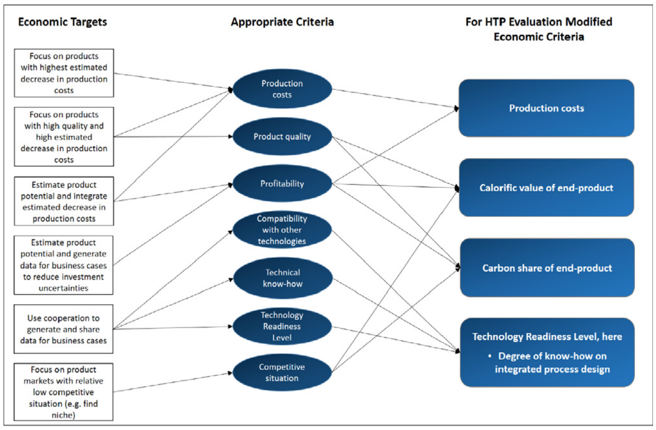

Fig. 5. Process diagram for the derivation of economic criteria.

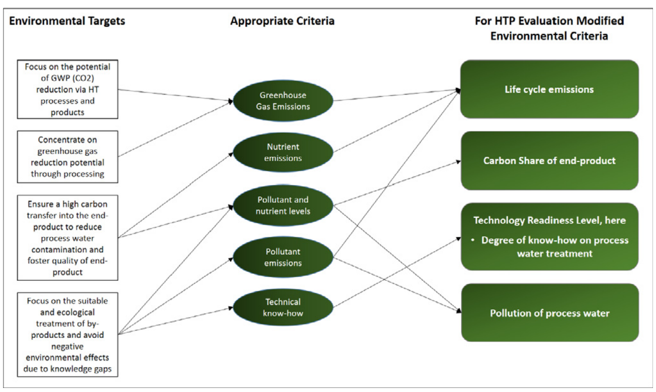

Fig. 6. Process diagram for the derivation of environmental criteria.

Because the importance of integrated phosphorus recycling during the processes was mentioned multiple, an additional criterion for "*recycled phosphorus*" is introduced.

The relevant criteria to assess the potential for HTP as options for the treatment of biogenic residues as well as their measurement units are presented in Table 10 as summarizing overview. It is differentiated between input and output metrics. Input metrics represent criteria that must be minimized, whereas output metrics represent criteria that should be maximized to enhance efficiency. The dry matter content of the substrates represents a K.O. criterion because a specific range is necessary for HTP to become a suitable treatment option.

4. Discussion

By connecting the general criteria from technology and sustainably assessment with the targets derived from the SWOT analysis (Figs. 4–6) it becomes possible to select specific criteria which reflect technology specific potentials and barriers for the chosen dimensions. Because the relevant information was identified with an expert survey, workshop and literature review the criteria are objective and transparent.

Considering the number of mentioned potentials and barriers and the derived SWOT targets a focus is set on criteria for the technological dimension. Especially the TRL seems to be an essential assessment criterion, which shows the high number of addressed targets. Based on the identified criteria of this analysis, a next step will be to prove the availability and quality of needed data and check the independency of the criteria to each other for specific cases (see step 7 of the methodology).

Most selected criteria are measurable on a cardinal scale. Just the TRL assessment depends on an ordinal scale, which means that the measured elements can be ranked but no quantifiable differences between these ranks can be measured (David and Nagaraja,

Table 10
Identified criteria for evaluating HTP as options for the management of biogenic residues including measurement scales & units and target values/ranges.

Criteria	Definition	Unit	Relevant process step	Number of targets addressed
Dry matter content of substrates	The relation of organic dry matter to water content of the substrate. Recent studies recommend an organic dry matter content between 10 and 30% for optimal processing. If this range is not fulfilled the considered substrate is not suitable and hence the alternative may be excluded from the analysis (Reißmann et al., 2018).	Percent of organic dry matter content	Feedstock provision	2
Production costs of final product	Raw material costs and manufacturing costs of the product (e.g. hydro-coal) (Bronner, 2013).	Euro per mass unit (e.g. kilogram)	Feedstock provision and conversion/refinement	4
Distance of plant to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Distance unit (e.g. meter)	Feedstock provision	2
Degree of pollution of process water	Share of organic substances in residual water that occurs after hydrothermal processing (Fettig et al., 2015).	mgO_2/L (COD value)	By-products	2
Process life cycle emissions	GHG emissions occurring through the process steps relating to the system boundaries (ISO, 2006).	Global Warming Potential (CO_2 equivalent)	All process steps	2
Output metrics				
Technology Readiness Level	Classification of the level of development of a considered technology according to ISO 16290 (ISO, 2013).	Assessed on a scale from 1 to 9 (cf. Mankins, 1995)	All process steps	6
Material efficiency (-balance)	Relation of product output to raw material input (Eichhorn, 2000).	Percent of mass unit	Conversion/refinement	1
Energy efficiency (-balance)	Relation of energy output to energy input (Eichhorn, 2000).	Percent of energy unit (e.g. Mega Joule)	Conversion/refinement	1

(continued on next page)

Table 10 (*continued*)

Criteria	Definition	Unit	Relevant process step	Number of targets addressed
Calorific value of final product	Maximum usable heat amount through the combustion of the final product (coal, oil or gas) (Brandt, 2004).	Mega Joule (MJ) per mass unit	Product Usage	4
Carbon share of final product	Share of carbon in HTC coal in relation to total mass volume of final product.	Percent	Product Usage	4
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total phosphorus substrate feed-in.	Percent	Recycling	2

2003). This is of importance for the selection of a suitable assessment method because for some methods scales must be adapted if attributes depend on an ordinal scale (cf. Peters and Zelewski, 2007). Only for the moisture content of the substrate, a target range exist which is why this criterion has been identified as a K.O. criterion. For this reason the range must be fulfilled to ensure an economic processing (Vogel, 2016; Greve et al., 2014).

From a methodological point of view, it can be determined that instruments from strategy development seem suitable for a structured development of evaluation and assessment criteria of technologies, if the overall target – in this case the technologies suitability for the treatment of biogenic residues – is clearly specified. Hence, the introduced method is also transferable for other contexts of criteria development. The most critical step for a successful criteria development is the collection of information. We recommend to integrate estimations of relevant experts next to a general literature investigation. In this analysis, many potentials and barriers have been identified based solely on expert estimations.

Regarding the goal of this work, it was shown how this approach can be used to develop technology specific assessment criteria for different evaluation dimensions. A central advantage of this method are the high transparency levels of the resulting criteria, which can be ensured through the integration of several independent experts.

A shortcoming is the relative high effort for the information collection procedure. However, especially for new and emerging technologies this effort will be very worthwhile because the information can be also used for additional purposes than criteria development, e.g. strategy development or qualitative technology forecasting. Mostly, SWOT analysis are common practice for companies and other entities. Hence, the application of this structured approach will be easy to integrate because a well-known instrument (SWOT analysis) can be used.

5. Conclusion

This analysis was carried out to present a transparent and structured approach for developing dedicated criteria to assess the suitability of HTP for treating biogenic residues. With the approach explained in section 2 it became possible to derive such criteria by using elements from strategy development, in particular SWOT analysis. The general approach can be used for different cases of criteria development unless that this study was focusing on HTP. In result, the most important assessment criteria seem to be the TRL, production costs and the carbon share and calorific value of the end-product. However, it should be considered that a slight tendency for the selection of criteria is connected with the selection of the expert panel. In this case, technology oriented stakeholder groups dominated which is a possible reason for the high importance of the criterion TRL. This is why it is recommendable to create an expert panel that represents mostly all stakeholders in a balanced way.

In many of the discussions carried out with experts in the field, one subject that prompted was the development of a tool based on multi-criteria analysis to transmit these criteria into a robust, transparent and holistic methodological framework. Such an instrument needs to be developed and tested for case studies to validate the applicability. The value-added of the instrument will be that the technologies of the HTP platform (HTC, HTL, HTG) will become comparable to each other and to specific reference systems (e.g. pyrolysis). Next to this, the assessment procedure will be able to compare the generic platform types based on average data as well as specific concepts based on real data from practice. It can be used by different stakeholder groups, e.g. for investment or funding decisions. Further studies will focus on developing such an assessment instrument or instruments to support future decisions in this field of technology. In particular, the use of such a multi-criteria analysis tool for assessing scenarios - that represent potential future pathways of HTP - will be an essential part of forthcoming studies.

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Paper III

The following text reassembles the full text-version of the article:

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Review Article

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How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal

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Abstract

A considerable amount of wet biogenic residues and waste has no resource-efficient use in several European countries yet. Hydrothermal processes (HTP) seem to be promising for treating such biomass as they best work with substrates with 70% to 90% water content. However, thus far the suitability of HTP for this purpose has not been sufficiently evaluated, for which this work aims to identify suitable multi-criteria analysis (MCA) methods that can be used to identify promising ways for the hydrothermal treatment of wet bio-waste. A review on 31 recent MCA studies in bio-waste management was conducted with the aim of comparing them to methodological requirements for evaluating HTP. Furthermore, an MCA approach for HTP based on the review findings is proposed. Results show that no observed MCA method is directly transferable for assessing HTP, for which a customized approach combining the analytical hierarchy process and the technique for order preference by similarity to ideal solutions is proposed and preliminarily validated with literature data. These preliminary calculations indicate that hydrothermal gasification seems most promising under consideration of multiple criteria using the available average and exemplary data. However, needless to say there is still a long way to go to obtain the sufficient adequate data to validate and use the model appropriately, for which further studies are necessary to acquire more reliable data and to assess also future technology developments of HTP.

Keywords

Review, hydrothermal processes, biogenic waste, multi-criteria analysis, analytical hierarchy process, technique for order preference by similarity to ideal solution

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Introduction

The efficient use of biogenic residues and waste can reduce costs and greenhouse gas emissions, save natural resources and promote climate protection (Eriksen et al,. 2017). Besides, such a utilization can foster the progress towards a bio-economy (cf. BMEL, 2014; European Commission, 2012) that aims at value-added treatment of biomass for producing materials, chemicals, fuels and energy in a sustainable manner and after providing sufficient food and feed for societal needs (Bezama, 2016; Thrän and Bezama, 2017). However, a considerable part of biogenic residues and waste is inefficiently (e.g. energetic use despite of low heating values) or not even used yet (cf. Brosowski et al., 2016; Pehlken et al., 2016; Tröger et al., 2013). A study that analysed twelve countries of the European Union focusing on the potential of biogenic residues for cellulosic biofuel production has shown that particularly France has high unused amounts of up to 60 million metric tonnes' dry matter per year. Forecasts for 2020 and 2030 even show that these quantities will increase for most of the observed countries (Searle and Malins, 2015). Considering this, the identification of suitable technological solutions for sustainably utilizing such bio-waste in future is of high interest for research and practice (cf. Eriksen et al., 2017; Parawira et al., 2008; Tröger et al., 2013). Previously, it was determined that especially the treatment of wet and sludgy substrates has gained rising attention in the last years (Reißmann et al., 2018). In contrast to solid bio-waste, wet and sludgy residues need an energy-intensive and cost-intensive pre-treatment (e.g. drying and thickening) to be suitable for conventional biomass treatment paths which impedes their usage. However, some biomass conversion processes are generally applicable to treat these residual streams (Zhang et al., 2014), for example, biochemical processes such as anaerobic digestion (AD) and thermochemical processes such as pyrolysis (Han et al., 2016; Poulsen et al., 2012; Wzorek and Tańczuk, 2015). Nonetheless,

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Table 1. Overview of hydrothermal processes (HTP) types (adapted from Reißmann et al., 2018).

HTP type	Brief definition	Process characteristics
Hydrothermal carbonization	Coalification process converting biogenic materials into hydro-char (Fiori and Lucian, 2017). Hydro-char is primarily used for energetic purposes, material applications and in agriculture as fertilizer or soil conditioner (Lu et al., 2012)	160–250°C 10–30 bar 1–72 hours
Hydrothermal liquefaction	Process transforming biogenic materials into chemicals and bio-oil (Zhang, 2010). Bio-oil is used as liquid fuel for energy production and as substitute for crude oil in the cosmetics and chemical industries (Kruse et al., 2013)	180–400°C 40–200 bar 10–240 minutes
Hydrothermal gasification	Process converting biomass into gaseous materials, primary methane and hydrogen. The main products are used for energy-generating purposes and for applications in the chemical industry (Kruse, 2009).	350–500°C 230–400 bar < 10 minutes

Table 2. Methodological sequence of the study.

Steps	Aims	Methods
1 Review	Identification of most common multi-criteria analysis (MCA) methods in waste management and bio-waste management	Search strategy-based review
2 Applicability check	Proofing applicability of MCA methods for evaluating hydrothermal processes (HTP)	Checklist with methodological requirements for HTP assessment
3 Methods development	Proposing a tailor-made MCA procedure for HTP. Preliminary validation of the proposed approach with data from the literature	Adaption and/or combination of MCA methods within an assessment approach fulfilling the methodological requirements

shortcomings are connected to the mentioned treatment paths which impede the decision for the optimal solution (e.g. difficulties due to high pollutant/nutrient contents) (Nielfa et al., 2015; Prabhu and Mutnuri, 2016; Rulkens, 2008; Saxena et al., 2009). Besides, while most biomass with a high moisture content were treated via AD for energetic purposes in the past, requirements of the European Waste Framework Directive have prioritized a material treatment before an energetic use since 2008 (European Union, 2008). Thus, processes that include material fields of application are of certain interest. Due to these obstacles and requirements, substantial amounts of wet biogenic residues are not in use yet or will need new ways of treatment in future. Activities in research and practice indicate that hydrothermal processes (HTP) seem to be promising paths for transforming wet biomass into gaseous, liquid or solid carbon containing products by thermochemical conversion (Hallesche Stadt und Wasserwirtschaft, 2015; Kruse et al., 2013; Libra et al., 2011; Lin et al., 2017). The procedure needs high water containing substrates for optimal processing, which is why materials such as sewage sludge are particularly suitable (Greve et al., 2014). Depending on the process parameters (temperature, pressure and residence time) different HTP types occur (Table 1).

The suitability for the hydrothermal treatment of wet bio-waste has not been sufficiently evaluated yet. Hence, there is a particular interest for a tailor-made assessment approach (cf. Reißmann et al., 2018: 248). A stakeholder workshop carried out in September 2016 in Leipzig, Germany (cf. DBFZ, 2016) showed the need of an assessment tool considering multiple attributes. Most stakeholders argued that the assessment of HTP by multiple criteria will help to reduce uncertainty for decision-making regarding funding and investment but also to identify research priorities for HTP. However, most current studies concentrate on single aspects such as optimization of process parameters (cf. Aggrey et al., 2012; Elliot, 2008; Klingler and Vogler, 2010), economic assessment (cf. US Department of Energy, 2014, 2016) or life cycle assessment (cf. Ahamed et al., 2016; Bennion et al., 2015). But to recommend promising technology development paths based on scenarios (e.g. increase of full-scale HTP plants in Europe due to implementation of cost-effective treatment for process water), a suitable multi-criteria assessment tool indicating if HTP are still promising based on computations with data on economic, environmental and technological aspects seems useful. Thus, the question that rises is how it will be possible to identify the most suitable ways for the hydrothermal treatment of wet bio-waste by considering multiple attributes.

This study wants to contribute to the solution of this question. Therefore, the goals of this work are: providing an overview of MCA methods commonly used in bio-waste management research; defining necessary requirements to evaluate HTP in a systematic way; and analysing if commonly used MCA methods fulfil these requirements and *if not* proposing an MCA approach to evaluate HTP for managing wet biogenic residues that fulfils all requirements.

Materials and methods

The work was organized in three steps as presented in Table 2.

Table 3. Search strategy.

Category	Specification	Reason for specification
Considered time period	Sources not older than five years	Only most recent MCA methods should be identified
Considered sources	Google, Google Scholar, Scopus, Science Direct	Most common search engines for scientific purposes
Considered document types	Scientific articles, conference proceedings, books and book chapters	Most common document types for publishing scientific analysis
Search terms	Multi-criteria analysis (MCA) waste management; MCA bio-waste management; multi-criteria decision-making waste management	Search terms were defined with respect to the aim of step 1

Step 1: review

A literature review was executed to identify the most commonly used MCA methods in bio-waste management research by applying a structured search strategy (Table 3).

About 90 studies were identified. However, documents had to be excluded due to missing details regarding the MCA methods used and an insufficient focus on bio-waste management contexts. In all, 31 documents were reviewed with regard to the MCA methods used.

Step 2: applicability check

The suitability of the identified methods is assessed by using a checklist on methodological requirements. For this, a point scale is used to assess the level of suitability, that is, 2 points mean that the requirement is fulfilled, 1 point means that the requirement is in part fulfilled and 0 points mean that the requirement is not fulfilled.

Step 3: methods development

If no considered MCA method fulfils all requirements, this means that no method is directly transferable for evaluating HTP. Hence, a tailor-made approach for HTP will be proposed. For this, most suitable MCA methods will be combined and/or adapted in an overall technology assessment (TA) procedure.

Results and discussion

Review on MCA studies in bio-waste management

Thirty-one studies were analysed of which four are review articles. Table 4 shows the thematic focus and applied MCA methods of the observed studies.

None of the assessed studies is focusing on bio-waste management which indicates the lack of MCA approaches for this field of study. In contrast, 39% of the studies focus on municipal solid waste management. Thus, in most studies bio-waste is at least partly regarded as if it is a fraction of municipal solid waste. However, the management of wet and sludgy biogenic residues is not considered by the observed studies. For healthcare waste (13%), industrial waste (13%) and management issues (19%) such as site selection, waste collection and paper waste management MCA methods are applied too. The review results show once more the necessity of a customized MCA approach for HTP, because no appropriate MCA approaches exist for relative fields such as the assessment of technologies for the management of wet bio-waste in general.

Most studies use the analytical hierarchy process (AHP) (42%) which is also confirmed by the observed review articles (cf. Achillas et al., 2013; Coelho et al., 2017; Mardani et al., 2015; Soltani et al., 2015). However, also combined methods are applied by 23% of the studies. Table 5 describes the considered methods and combinations/adaptions briefly.

Because none of the considered MCA is focusing on bio-waste management, this analysis will provide novel information on the suitability of MCA methods for bio-waste management especially for the hydrothermal processing of wet biogenic materials.

Applicability check of identified MCA methods

To check the applicability of the identified MCA methods for evaluating HTP, methodological requirements must be defined. General requirements are transparency, consistency and transferability (cf. Billig, 2016; DFG, 2013; Ganzevles and van Est, 2012; Scheffzcik, 2003). Besides, the following aspects have to be fulfilled by a suitable method for evaluating HTP:

Holistic nature: thermo-chemical and bio-chemical biomass conversion technologies and energetic as well as material treatment paths can be considered.

Multi-dimensionality: quantitative and qualitative techno-economic and environmental attributes can be considered simultaneously.

Applicability: the method is easy to apply also without detailed background knowledge (e.g. for calculations).

Objectivity: the selection and weighting of criteria involves stakeholder/experts to ensure transparency, relevance and objectivity of criteria.

Adaptability: the procedure is iterative, to make steps repeatable and adaptable.

Table 4. Thematic focus and multi-criteria analysis (MCA) methods of observed studies.

Thematic focus	Applied MCA method	Corresponding studies	Additional information
General focus	Analytical hierarchy process (AHP)	Milutinović et al. (2017)	–
		Achillas et al. (2013)	79 articles reviewed by this study
	Fuzzy AHP	Zare et al. (2016)	–
	Preference ranking organization method for enrichment evaluations (PROMETHEE)	Makan et al. (2013)	–
	Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	Opricovic and Miloradov (2016)	–
Municipal solid waste	AHP	Milutinović et al. (2014)	–
		Antonopoulos et al. (2014)	–
		Soltani et al. (2015)	68 articles reviewed by this study
		Thampi and Rao (2014)	–
		Vučijak et al. (2016)	–
	Technique for order preference by similarity to ideal solution (TOPSIS)	Nouri et al. (2014)	–
		Jovanovic et al. (2016)	–
		Klavenieks et al. (2017)	–
		Asefi and Lim (2017)	–
	PROMETHEE	Panagiotidou et al. (2015)	–
	Quality function deployment	Santos et al. (2017)	–
	Combined method	Herva and Roca (2013)	Combination of AHP and PROMETHEE
Industrial waste	AHP	Nouri et al. (2018)	–
		Coelho et al. (2017)	260 articles reviewed by this study
	Combined method	Mir et al. (2016)	Combination of TOPSIS and VIKOR
		Chauhan and Singh (2016)	Combination of fuzzy AHP and fuzzy TOPSIS
Healthcare waste	AHP	Yap and Nixon (2015)	–
		Mardani et al. (2015)	393 articles reviewed by this study
	Fuzzy VIKOR	Liu et al. (2013)	–
	Combined method	Hariz et al. (2017)	Combination of AHP, VIKOR and PROMETHEE
Waste management issues	VIKOR	Liu et al. (2014)	–
	AHP	Ferreira et al. (2015)	–
		Majumdar et al. (2017)	–
	Fuzzy decision-making trial and evaluation laboratory	Wang et al. (2018)	–
	Combined method	Arıkan et al. (2017)	Combination of fuzzy TOPSIS and PROMETHEE
		Shahba et al. (2017)	Combination of AHP and TOPSIS

Benchmarking: target values considering certain requirements can be determined.

The identified MCA methods were checked with regard to the mentioned requirements (Table 6). Fuzzy logic MCA and combined methods were not considered as they do not represent own MCA methods but adaptions, extensions and combinations of them. As mentioned, a point scale from 0 to 2 was used to assess the MCA methods regarding requirement fulfilment. Details for the rating are described in the supplementary information (SI) file.

Results show that no identified MCA method fulfils all requirements and is therefore directly applicable to HTP evaluation. Thus, a combined method including most useful elements of the considered MCA approaches must be developed to reach a higher degree of fulfilment. AHP, preference ranking organization method for enrichment evaluations (PROMETHEE) and technique for order preference by similarity to ideal solution (TOPSIS) seem most suitable because they already reach high degrees of fulfilment. They fulfil the requirements of holistic nature, applicability and adaptability. The requirement multi-dimensionality is in part fulfilled through these methods. Qualitative criteria are considered if they are measurable on an ordinal scale (i.e. a scale with similar distances). Hence, nominal values (e.g. “yes” or “no” attributes) cannot be considered by the methods. However, most criteria values are at least ordinal. Regarding the requirement of objectivity, the AHP seems more suitable because expert involvement is usually part of the criteria weighting. Further, a criteria selection or weighting procedure is not part of PROMETHEE and TOPSIS at all. Hence, for criteria weighting the AHP should be used. However, for determining criteria, AHP, PROMETHEE and TOPSIS include no expert involvement. This is why an own approach for a more objective criteria determination was previously developed. Regarding benchmarking, AHP, PROMETHEE and TOPSIS can be enlarged

Table 5. Descriptions of the multi-criteria analysis (MCA) methods used by the observed studies.

MCA method	Description	Reference
Analytical hierarchy process	Identification of preferences by pair-wise comparisons of criteria using a procedural sequence. Criteria are sorted hierarchically	Saaty (1987)
Decision-making trial and evaluation laboratory	Analysing and solving complex and intertwined problems by verifying interdependence between variables. Improving them by creating a specific chart to reflect interrelationships between variables	Fontela and Gabus (1976)
Preference ranking organization method for enrichment evaluations	Multi-criteria decision-making by building of an outranking between different alternatives	Brans et al. (1986)
Quality function deployment (QFD)	Several quality criteria are combined within a QFD matrix to show correlations. Aim is to identify products and services that are desired by customers under consideration of multiple criteria	Akao (1992)
Technique for order preference by similarity to ideal solution	The advantageousness of an alternative is assessed by determining the distance to the (virtual) best and worst alternative	Hwang and Yoon (1981)
Vise Kriterijumska Optimizacija I Kompromisno Resenje	Multi-criteria optimization of complex systems based on ranking and selecting from a set of alternatives considering conflicting criteria. The ranking is performed by comparing the measure of closeness to the ideal alternative	Opricovic (1998)
Fuzzy logic MCA	MCA that deal with unclear information (fuzziness). In general, all of the above-mentioned MCA can be enlarged with fuzzy logic	Abdullah (2013)
Combined methods	The MCA combine two or more of the above-mentioned methods within a common technology assessment procedure	–

Table 6. Comparison of multi-criteria analysis methods regarding requirement fulfilment.

	Analytical hierarchy process	Decision-making trial and evaluation laboratory	Preference ranking organization method for enrichment evaluation	Quality function deployment	Technique for order preference by similarity to ideal solution	Vise Kriterijumska Optimizacija I Kompromisno Resenje
Holistic nature	2	2	2	1	2	2
Multi-dimensionality	1	2	1	2	1	1
Applicability	2	1	2	1	2	1
Objectivity	1	0	1	1	1	1
Adaptability	2	1	2	1	2	2
Benchmarking	1	0	1	0	1	1
Degree of fulfilment (absolute)	9/12	6/12	9/12	6/12	9/12	8/12
Degree of fulfilment (relative)	75%	50%	75%	50%	75%	66%

with a sensitivity analysis to determine potential thresholds or to test scenarios. Thus, the aimed for method should also include a sensitivity analysis. Especially, because of its higher applicability and the more intuitive interpretability of the results compared to the AHP and PROMETHEE, TOPSIS will be used for the comparison of alternatives.

Proposed MCA procedure for evaluating HTP

Previous results indicate the lack of sufficiently suitable MCA methods for HTP assessment which is why a tailor-made procedure is proposed. This method will assess HTP to each other and relevant reference systems by considering multiple attributes for the first time. The following step-wise and iterative procedure was developed. Because the basic procedure is structured as a TA framework, the approach is in part transferable to comparable evaluations of biomass conversion processes.

The technology "fact sheet": setting the investigation framework and describing the considered technologies. To get consistent, interpretable and transparent results, first it is necessary to set an investigation framework which defines evaluation purpose, system boundaries and considered time period. Further, most important technology characteristics must be described to enhance the transparency and thus the interpretability of the results. After which, the system boundaries of the considered technologies must be set. The system can contain: (1) feedstock provision and pre-treatment; (2) conversion and refinement; (3) products and by-products; (4) logistics and distribution; (5) product usage; and (6) deposition or re-use/recycling (end-of-life). This is especially important to define suitable reference systems, for example, if no products are considered, reference systems must not necessarily operate on competitive product markets. Often it is not needed to consider all system components because of an already specific assessment purpose. In addition, the decision for including system components depends on data availability, which is why system boundaries are often limited. It is crucial to check data availability on system components and set them in context to the necessity of including them. Several TA studies recommend that effort and benefits of the analysis must be in balance to ensure the applicability (cf. Billig and Thrän, 2016, 2017; Hall, 2012). After defining the system boundaries, suitable reference systems must be determined to enhance the interpretability of results. For HTP, the determined reference systems should be competitors for the same substrates that could be utilized through HTP and/or operate at the same product markets. Depending on the analysis focus the general TA procedure can be adopted at this point (e.g. if specific conversion efficiencies are compared). However, the definition of reference systems depends on the assessment purpose and must consider the investigation framework, technology characteristics and system boundaries. In general, the comparability of the considered technologies must be carefully checked at this point. The results of this step can be summarized in a technology "fact sheet" (cf. SI).

Developing and selecting technology-specific assessment criteria. Suitable assessment criteria are crucial to ensure significant results. Criteria must fulfil requirements such as objectivity, consistency, adaptability, transparency and non-redundancy. Also, reliable data should be available. The criteria shall represent the assessment object nearly in complete (Rohweder et al., 2015) and should have minimal influence to each other. However, a total independency cannot be reached in practice (Billig, 2016). The development of metrics for MCA is usually carried out in a less structured way and through a limited number of primary internal experts (e.g. project team members). Although some guidelines and examples recommend selection factors which can be used, the integration of relevant stakeholders into criteria development is often limited to criteria prioritization (cf. Akadiri and Olomolaiye, 2012; Akadiri et al., 2013; Valenzuela-Venegas et al., 2016). To foster objectivity and transparency of criteria derivation, the authors recommend a structured process using instruments from strategy development for the transparent selection of dedicated assessment criteria (cf. Figure 1, step 2). The derived criteria can be seen as a "long list". This means, depending on the specifications in the "fact sheet", only a part of the criteria will be used for the actual assessment. It is recommendable to use a decision chart for the final selection of criteria which depends on the analysis case. Finally, only a selection of criteria from the "long list" are taken into account for the analysis.

Multi-criteria decision-making and sensitivity analysis. To weight the selected criteria the AHP will be used. The basic procedure includes the following steps according to Saaty (1990): creating the decision hierarchy; making pair-wise comparisons of decision-making parameters (criteria and alternatives); calculating priorities of decision-making parameters; and check consistency. For the proposed procedure, an adapted AHP is used. This means, only the second and third step is executed. The first step is skipped, because the decision hierarchy is created through the previous steps of the overall procedure and evaluation criteria are already selected. The comparison of alternatives is part of TOPSIS and thus also excluded at this point. Thus, the AHP is primarily applied for derivation of criteria weightings. It is recommendable to use expert estimations to generate the weightings. For this, pair-wise comparisons of all criteria c_i to each other have to be carried out. To select the expert estimations a Delphi survey can be applied. The Delphi method is a systematic survey scheme with multiple steps containing feedback loops. The aim of this method is to reduce misjudgements of experts by applying the survey at least two times (Rowe and Wright, 1999).

After executing the AHP, the consistency of the weightings has to be checked. This means, if the criteria are ranked like A > B > C then also A > C must be valid (Saaty, 1987). However, this form of consistency is often not fulfilled if several criteria and criteria relations are part of the analysis. For this, Saaty (1987) has developed the consistency index ($C.I.$) and the consistency ratio ($C.R.$) which can be calculated with AHP software by using the maximum eigenvalue (λ_{max}) of the corresponding eigenvector. Equation (1) must be used:

$$\begin{aligned} C.I. &= \frac{\lambda_{max} - n_z}{n_z - 1} \\ C.R. &= \frac{C.I.}{R.I.} \text{ with } C.R. < 0.1 \text{ to ensure consistency.} \end{aligned} \tag{1}$$

$R.I.$ means random index which is an average $C.I.$ of randomly reciprocal matrices. The $R.I.$ is given by Saaty (1987) with regard to the number of criteria.

The weighted criteria are furthermore used in TOPSIS. In TOPSIS, a set of different decision alternatives are compared in relation to each other by using multiple criteria and taking the best-case and worst-case as benchmarks (Hwang and Yoon, 1981). Thus, the best alternative in relation to other ones that are part of the analysis is calculated. This is why these types of MCA are also named multi-attribute decision-making with a discrete solution space (Geldermann and Lerche, 2014). The more alternatives and criteria are applied the significance of TOPSIS' results rises accordingly. However, also the effort for the application of this method rises with a higher number of alternatives and

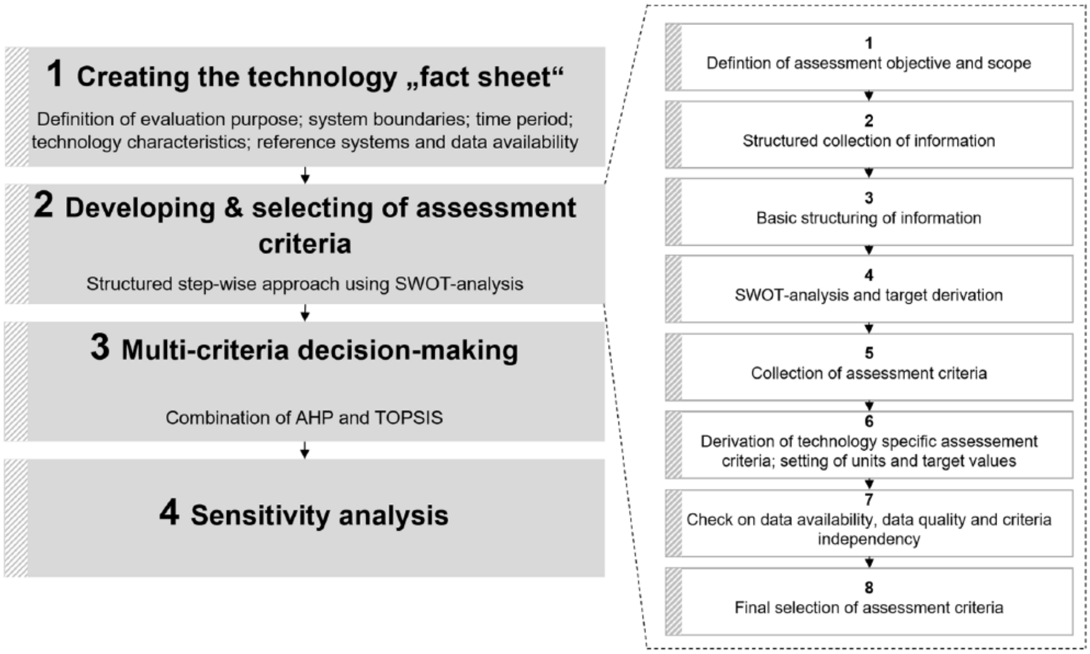

Figure 1. Methodological sequence of multi-criteria analysis approach for assessing hydrothermal processes.

criteria which is why a useful balance between significance and effort must be considered regarding the assessment objectives. In comparison to classical MCA methods such as utility analysis, TOPSIS is able to handle a high number of criteria if preferences are not fully clear. Thus, this assumption of TOPSIS adequately represents reality and needs less information from the decision-maker (Geldermann and Lerche, 2014). Further, TOPSIS needs just the criteria weightings as input from the decision-maker which is why the procedure is relatively easy to apply in practice. TOPSIS is carried out according to the procedure of Hwang and Yoon (1981). After calculating the efficiency values c_i, the criteria values and/or the criteria weightings can be varied to show the sensitivity of these parameters on the results (*ceteris paribus*). Thus, thresholds and benchmarks can be calculated that indicate which values are optimal to reach the best-case frontier for a certain alternative. By creating scenarios that determine specific values for the future also the effects of this on the efficiency of the considered alternative can be shown by adapting the parameter in TOPSIS.

Preliminary method validation. To check the applicability of the procedure a preliminary method validation was executed. Because a large data survey has not been carried out so far, the authors use average data on HTP archetypes identified by a literature review (cf. KIC InnoEnergy, 2015; Klemm et al., 2009; Reißmann et al., 2018; Stafford et al., 2017). It has to be mentioned that this preliminary calculation was just carried out to validate the model and the results are not reliable so far. Especially, the comparability of calculations made for data on production costs or life cycle emissions need to be carefully proven for all considered technologies. For this exemplary case, such an extensive proofing was not carried out which is why the first results are not scientifically reliable yet. For the criteria weighting an expert survey has to be carried out. Currently, the survey is not finished which is why "estimated" weightings have to be used for this validation. The estimated weightings result from literature information (cf. Reißmann et al., 2018) and first expert estimations made during a workshop in September 2016 in Leipzig, Germany (cf. DBFZ, 2016).

First, the technology fact sheet was created for the observed HTP archetypes and the corresponding reference system (see SI). Second, relevant criteria ("long-list") were derived through the approach described previously (see SI). This "long-list" was further concentrated on suitable criteria using the illustrated decision chart (Figure 2).

The resulting criteria and their corresponding weightings are shown in Table 7.

By using these criteria in TOPSIS for data of hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), hydrothermal gasification (HTG) and AD archetypes, the following values for the relative distances c_i result. The data are part of the SI.

Rank 1: HTG – c_i -value of 0.66
Rank 2: AD – c_i -value of 0.48
Rank 3: HTC – c_i -value of 0.32
Rank 4: HTL – c_i -value of 0.26

The exemplary results show that HTG is most beneficial under consideration of multiple techno-economic and environmental attributes. This result seems robust because HTG has the best values regarding life cycle emissions and production costs. Both criteria have a relatively high weighting which shows the importance of these values. Although HTG has the lowest current technology readiness level (TRL) compared to the other alternatives, the MCA procedure indicates that this technology is still

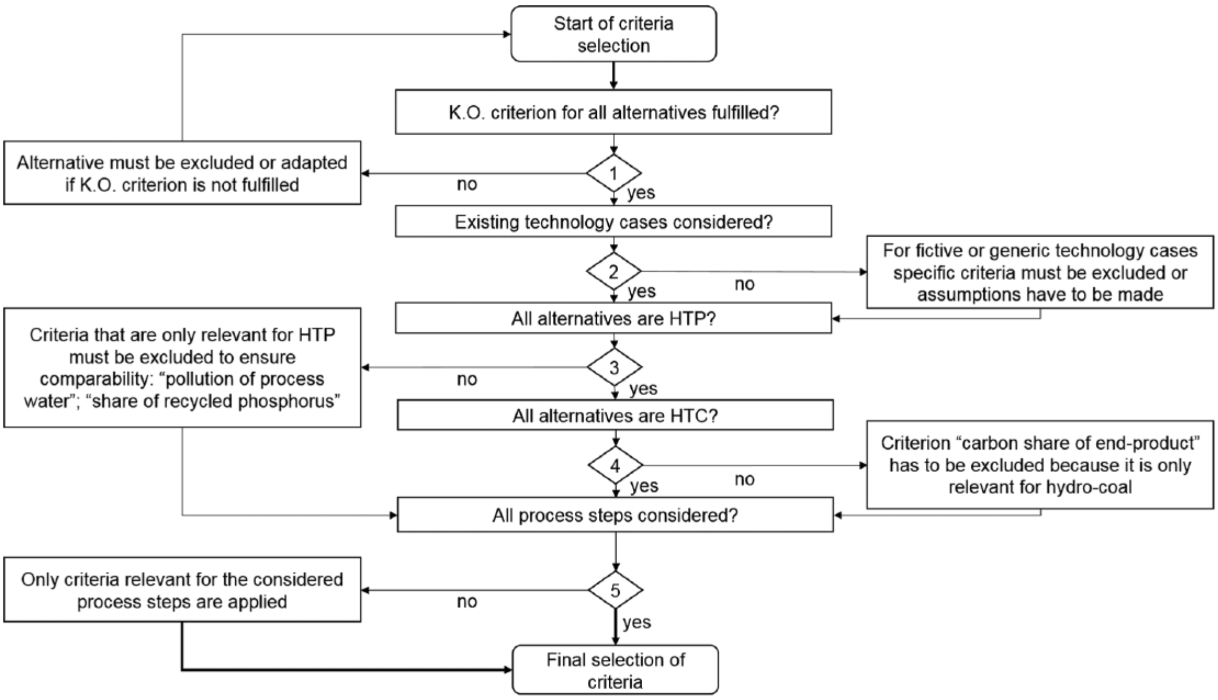

Figure 2. Decision chart for preliminary method application.

Table 7. Selected criteria for preliminary method application.

Criteria	Unit	Weighting	
Production costs	EURct/kWh	20%	Inputs
Life cycle emissions	gCO2eq./$MJ_{product}$	18.5%	
Technology readiness level	–	40%	Outputs
Material efficiency	% kg	7.5%	
Energy efficiency	% MJ	9%	
Calorific value of end-product	MJ/kg dry matter	5%	

promising. However, especially the weightings are of high importance. Thus, they have to be chosen very carefully. Figure 3 illustrates the important influence of criteria weightings exemplary for TRL assuming a proportional increase of all corresponding criteria weightings (sensitivity analysis).

Comparison of study findings to comparable work

One particular issue about this field of work is that up to this date, no further multi-criteria approaches have been developed for assessing the suitability of hydrothermal processing wet bio-waste. Thus, this work provides novel information on how to deal with this issue by using an assessment framework that considers multiple attributes and specific requirements on HTP. However, as already mentioned in the introduction section several other studies assessed the hydrothermal treatment of wet bio-waste and residues using different assessment approaches mostly concentrating on just one dimension (e.g. life cycle assessment or economic assessment). Such studies are important for the proposed MCA approach, because generated data on economic or environmental assessment can be used as input for the calculations if they are comparable to each other. However, none of these studies assessed HTP in a multi-dimensional way.

Only a few recent studies have proposed assessment approaches for biomass conversion systems considering multiple attributes. Suwelack and Wüst (2015) developed a unified appraisal framework for biomass conversion systems that includes a MCA approach based on standardized data and impact levels. The approach was tested on random data for three biomass conversion systems considering seven criteria on social, environmental and economic issues. In general, this approach can be used to assess HTP if reliable data are available. However, the framework is not customized for HTP which is why the criteria are more general and specific methodological requirements for HTP evaluation are not considered. Very important criteria for HTP, for example, process water pollution levels, are missing. The study of Billig and Thrän (2016) proposed an MCA approach to assess different bio-methane technology options. Also this approach seems transferable to some HTP concepts, especially HTG which also produces bio-methane. However, also in this approach relevant attributes and requirements for HTP

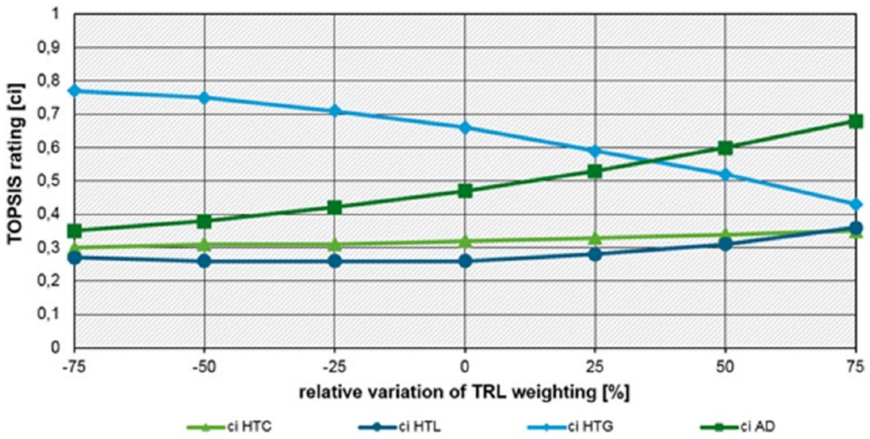

Figure 3. Sensitivity analysis for relative distance to ideal solution in relation to technology readiness level.

assessment are missing which further confirms the necessity of the tailor-made MCA framework proposed by this study. Other recent studies suggesting multi-dimensional assessment frameworks for biomass conversion technologies (Fazlollahi and Maréchal, 2013; Gassner and Maréchal, 2009; Martínez and Narváez, 2016) are also lacking in terms of missing criteria and having less consideration of the requirements for HTP evaluation.

Future perspectives and practical implications

Only a few industrial scale applications of HTP plants have been implemented in Europe, which is particularly due to techno-economic difficulties (cf. Reißmann et al., 2018). Hence, the primary aim is to use this MCA tool for a comparative evaluation of different scenarios that assume full-scale application of HTP under certain requirements. Using the MCA approach, these scenarios can be compared regarding several relevant criteria. By varying criteria values for these scenarios, efficiency ranges can be identified which further indicate promising target corridors for future technology development and research priorities. For example, these indications can help policy to decide on which solutions for HTP process water treatment public funding may focus on. In addition, decisions on regulatory adjustments, for example, for the standardization of HTP products, can be partly based on promising development paths indicated by the MCA (e.g. energy carrier or material application markets). For private investors, indications on promising future technology paths and corresponding criteria value ranges will help them to decide on investments for certain technological solutions considering specific requirements. In practice, the tool can be used for HTP site decisions (e.g. in relation to substrate availability), and decisions on plant scale and promising markets. However, the tool will become more relevant for practice if more industrial scale plants are established. This is because the framework assumes that a functioning market exists and industrial scale plants operate under economic conditions.

Conclusion

This analysis proposed an MCA framework to assess the suitability of options for the hydrothermal treatment of wet bio-waste. To better validate the applicability of the method, exhaustive data computations have to be made. A major advantage of the procedure is that it needs relatively less input from the user. For example, developing the criteria "long list" and criteria weightings must usually be executed just once and can be used for several analyses after. Thus, criteria derivation and weighting can be provided by experts before the user applies the approach for a case study or scenario analysis. TOPSIS is relatively easy to apply and the calculations can be made with Excel. However, the more criteria and alternatives that are considered the complexity of calculations rises. Due to the relatively easy understandable approach, the results of the analysis are good to interpret and to communicate to the target audience. However, also some shortcomings are connected to the approach. A specific disadvantage of TOPSIS is that criteria must at least be ordinally measurable with similar distances on the measurement scale. This is sometimes not given and thus such criteria would not be applicable in TOPSIS. However, this problem can be solved by applying height preferences (e.g. through utility functions). Further, data are sometimes not available for relevant criteria. This is especially reasoned in the novelty of the technologies that are connected to an insufficient data situation. Hence, it seems useful to enlarge the approach with fuzzy logic or by means of a complementary self-learning algorithm. Additionally, it is important to carefully check the primary data sources for the used criteria on their comparability (e.g. checking if comparable assumptions were made to calculate these data).

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Supplementary Information (SI) to article "How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal"

Appendix A – Check of MCA methods on requirement fulfilment

Analytical Hierarchy Process (AHP):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of AHP that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of AHP that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if data availability is given, all quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – qualitative criteria can be used but must at least be measurable on an ordinal scale.
Applicability	*Yes* – the AHP is a relative complex method because mathematical knowledge is necessary to solve matrix calculations. However, several software programs can assist to solve the calculations. Because the AHP is often applied in science and practice the applicability must be given.
Objectivity	Involvement of expert feedback in criteria selection: *No* – the criteria selection is applied by the decision-maker, expert involvement is not an integral part. Also, current applications do not involve experts into the criteria selection.
	Involvement of expert feedback in criteria weighting: *No/Yes* – as suggested by Saaty, the original version of AHP does not need expert involvement for criteria weighting because this is made by the decision-maker. Current applications try to the involve experts through surveys (e.g. Delphi surveys).
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of the classic AHP. However, subsequent sensitivity analysis are sometimes applied to interpret the results of AHP. Through this form of analysis also benchmarks can be generated.

Decision-Making Trial and Evaluation Laboratory (DEMATEL):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of DEMATEL that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of DEMATEL that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* –quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *Yes* – because DEMATEL primary measures the interdependencies between criteria through expert estimations, it is not necessary that all criteria are quantitative. Hence also qualitative criteria can be considered.
Applicability	*No/Yes* – the procedure itself is relatively simple and needs no in-depth mathematical knowledge to be applied. However, because expert involvement is needed to estimate the interdependencies of criteria the effort is relatively high.
Objectivity	Involvement of expert feedback in criteria selection: *No* – criteria selection is not a part of DEMATEL. Given criteria are checked regarding their independencies.
	Involvement of expert feedback in criteria weighting: *No* – also criteria weighting is no part of DEMATEL.
Adaptability	*No/Yes* – after expert estimations have been made it is very difficult to adapt the procedure (e.g. through introducing of new criteria). However, further estimations can be made if necessary, but this increases the effort considerable.
Benchmarking	*No* – benchmarking is no part of DEMATEL.

Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of PROMETHEE that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of PROMETHEE that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if data is available, all quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – because PROMETHEE uses preference functions for all criteria also qualitative criteria can be considered. However, they must be at least ordinal.
Applicability	*Yes* – several software applications can assist to solve the calculations.
Objectivity	Involvement of expert feedback in criteria selection: *No* – criteria selection is not a part of PROMETHEE. Criteria must be already given.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by PROMETHEE and can be selected by the user. Hence, experts can be involved or not.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of the PROMETHEE. However, subsequent sensitivity analysis are sometimes applied to interpret the results. Hence, also benchmarks can be generated.

Quality Function Deployment (QFD):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *No/Yes* – there are no assumptions of QFD that forbid this. However, the house of quality (as comparison matrix between attributes of alternatives) is only useful for very similar alternatives because customer requirements are maybe not comparable.
	Consideration of energetic and material treatment paths: *No/Yes* – there are no assumptions of QFD that forbid this. However, the house of quality (as comparison matrix between alternatives) is only useful for very similar alternatives because customer requirements are maybe not comparable.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – due to that QFD simply sorts the criteria within a matrix and seeks for correlation (house of quality) all kind of criteria can be considered in general.
	Consideration of qualitative techno-economic and environmental criteria: *Yes* – due to that QFD simply sorts the criteria within a matrix and seeks for correlation (house of quality) all kind of criteria can be considered in general.
Applicability	*No/Yes* – QFD is a relative simple analytical method which can be used without complex mathematics. Generally no software applications are necessary. However, because the analysis is primary based on customer product expectations, a high effort for market research is necessary. Next to this, creating the house of quality is hard without detailed background knowledge on the procedure of QFD.
Objectivity	Involvement of expert feedback in criteria selection: *No/Yes* – usually the internal project members define the product functions as one side of criteria and the customer define their requirements as another part of criteria. An objective expert feedback on this selection is normally no part of QFD.
	Involvement of expert feedback in criteria weighting: *No/Yes* – prioritization of criteria is usually done by the team members and also not verified through expert feedback. However, also the team members are experts in their fields.
Adaptability	*No/Yes* – QFD is no flexible procedure, because it only depends on creating the house of quality. However, further customer estimations or product functions can be added which makes the procedure in part adaptable. Including further alternatives that are not competitive to the primary alternatives is difficult because product functions as well as customer expectations may not match which makes them not comparable.
Benchmarking	*No* – a benchmarking of weightings or criteria at it is intended for the HTP method is no part of QFD. Also subsequent sensitivity analysis are usually not applied after QFD.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of TOPSIS that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of TOPSIS that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if criteria are measurable on a cardinal scale all kind of quantitative criteria can be used.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – criteria must be cardinally measurable which is often not given for qualitative criteria. However, this can be met by using height preferences for creating at least ordinal scales with similar distances.
Applicability	*Yes* – TOPSIS is a very intuitive and relative simple procedure. No complex mathematics are necessary. Software applications are available for extensive calculations.
Objectivity	Involvement of expert feedback in criteria selection: *No* – expert feedback for criteria selection is no necessary part of TOPSIS.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by TOPSIS and can be selected by the user. Hence, experts can be involved or not.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of TOPSIS. However, subsequent sensitivity analysis are sometimes applied to interpret results. Hence, also benchmarks can be generated.

Vise Kriterijumska Optimizacija I Kompromisno. Resenje (VIKOR):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of VIKOR that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of VIKOR that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – all kind of quantitative criteria can be considered by VIKOR.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – qualitative criteria can be considered if they are at least measurable on an ordinal scale.
Applicability	*No/Yes* – VIKOR is more complex and therefore harder to understand than other comparable MCA methods which reduce the intuitive interpretation of results. However, several software applications can assist to solve the calculations which reduces the effort at least in part.
Objectivity	Involvement of expert feedback in criteria selection: *No* – expert feedback for criteria selection is no necessary part of VIKOR.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by VIKOR and can be selected by the user. Hence, experts can be involved or not. Usually, weights are defined due to preferences of the decision-maker.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of VIKOR. However, subsequent sensitivity analysis can be applied to interpret results and generate benchmarks.

Appendix B – Exemplary filled sample technology "fact sheet"

<table>
<tr><td>Evaluation purpose</td><td colspan="2">Assess the suitability of fictive HTP concepts on the use of wet biogenic residues.</td></tr>
<tr><td>Geographic framework</td><td colspan="2">Germany.</td></tr>
<tr><td>Time period</td><td colspan="2">No specific time period, because several data sets with different time frames were used for the fictive concepts.</td></tr>
<tr><td rowspan="24">Description of considered technology concepts</td><td colspan="2">Hydrothermal Carbonization concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>10-30 bars</td></tr>
<tr><td>Reactor temperature range</td><td>160-250 °C</td></tr>
<tr><td>Reaction time range</td><td>1-72 h</td></tr>
<tr><td>End-product</td><td>Hydro-coal</td></tr>
<tr><td colspan="2">Hydrothermal Liquefaction concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta, algae</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>40-200 bars</td></tr>
<tr><td>Reactor temperature range</td><td>180-400 °C</td></tr>
<tr><td>Reaction time range</td><td>10-240 min.</td></tr>
<tr><td>End-product</td><td>HTL-oil</td></tr>
<tr><td colspan="2">Hydrothermal Gasification concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>230-400 bars</td></tr>
<tr><td>Reactor temperature range</td><td>350-400 °C</td></tr>
<tr><td>Reaction time range</td><td>5-10 min.</td></tr>
<tr><td>End-product</td><td>HTG-gas</td></tr>
<tr><td rowspan="8">Reference system(s)</td><td colspan="2">Anaerobic Digestion (AD) as competitive system on substrate markets:</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, animal excreta</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>Ambient pressure</td></tr>
<tr><td>Reactor temperature range</td><td>32-65 °C</td></tr>
<tr><td>Reaction time range</td><td>35-80 days</td></tr>
<tr><td>End-product</td><td>Biogas</td></tr>
</table>

System boundaries	(1) Feedstock provision & substrate pre-treatment → (2) Conversion & Refinement → (3) Products & By-products → (4) Product Usage
Check on data availability	Data from scientific studies and technical reports. Data refers to specific case studies (e.g. modelled plants, demonstration and pilot plants, and laboratory tests) and average values.

Appendix C – Criteria "long list"

Criteria	Definition	Unit	Relevant process step
K.O. criterion (Fulfillment must be given for every assessment alternative)			
Dry matter content of substrates	The relation of organic dry matter to water content of the substrate. Recent studies recommend an organic dry matter content between 10 to 30 % for optimal processing. If this range is not fulfilled the considered substrate is not suitable and hence the alternative may be excluded from the analysis (Reißmann et al. 2018a).	Percent of organic dry matter content	Feedstock provision
Input metrics/costs (to be minimized)			
Production costs	Raw material costs and manufacturing costs of the product (e.g. hydro-coal) (Bronner 2013).	Euro per functional unit	Feedstock provision and conversion/ refinement
Distance to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Kilometer (km)	Feedstock provision
Pollution of process water	Share of organic substances in residual water that occurs after hydrothermal processing (Fettig et al. 2015).	mgO_2/L (COD value)	By-products
Life cycle emissions	Pollutant emissions occurring through the process steps relating to the system boundaries (ISO 2006).	Global Warming Potential (CO_2 equivalent)	All process steps
Output metrics/benefits (to be maximized)			
TRL	Classification of the level of development of a considered technology according to ISO 16290 (ISO 2013).	Assessed on a scale from 1 to 9	All process steps
Material efficiency	Relation of product output to raw material input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement
Energy efficiency	Relation of energy output to energy input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement
Calorific value of product	Maximum usable heat amount through the combustion of the end-product (coal, oil or gas) (Brandt 2004).	Mega Joule (MJ) per functional unit	Product Usage
Carbon share of end-product	Share of carbon in HTC coal in relation to total mass volume.	Percent	Product Usage
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in.	Percent	Recycling

Appendix D – Applied data for preliminary calculations

Definitions of data types

- *Specific data* means that these values refer to exemplary processes and plants
- *Average data* means that these values are the average of data from several (at least two) processes and plants
- *Generic data* means that these values are the result of comprehensive meta studies and mostly typical for the whole process type

Criteria	Unit	Data type	Value(s)	References
Data on HTC				
Production costs	EURct/kWh	average	6.5	Reißmann et al. 2018
Life cycle emissions	$gCO2eq./MJ_{product}$	specific	45	Reißmann et al. 2018
TRL	-	generic	6.5	KIC InnoEnergy 2015
Material efficiency	% kg	specific	16.5	GRENOL 2014
Energy efficiency	% MJ	average	80	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	average	24.5	Reißmann et al. 2018
Data on HTL				
Production costs	EURct/kWh	specific	11.8	Reißmann et al. 2018
Life cycle emissions	$gCO2eq./MJ_{product}$	specific	-5	Reißmann et al. 2018
TRL	-	generic	7	Stafford et al. 2017
Material efficiency	% kg	specific	80	Toor et al. 2010
Energy efficiency	% MJ	average	78	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	average	35	Reißmann et al. 2018
Data on HTG				
Production costs	EURct/kWh	specific	3	Reißmann et al. 2018
Life cycle emissions	$gCO2eq./MJ_{product}$	specific	-600	Reißmann et al. 2018
TRL	-	generic	5	Vogel 2016
Material efficiency	% kg	specific	26	Kumabe et al. 2017
Energy efficiency	% MJ	average	76.5	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	specific*	21.65	Elsayed et al. 2015
Data on AD				
Production costs	EURct/kWh	average	7.5	Bundesnetzagentur 2014
Life cycle emissions	$gCO2eq./MJ_{product}$	average	-140	Fehrenbach et al. 2009
TRL	-	generic	9	Bundesregierung 2014
Material efficiency	% kg	specific	13	Volkmann 2009
Energy efficiency	% MJ	average	48	Reißmann et al. 2018
Calorific value of end-product	MJ/kg dry matter	average	31.25	FNR 2014

*) calculated with conversion factor of conventional natural gas.

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Paper IV

The following text reassembles the full text-version of the article:

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Article

Key Development Factors of Hydrothermal Processes in Germany by 2030: A Fuzzy Logic Analysis

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Abstract: To increase resource efficiency, it is necessary to use biogenic residues in the most efficient and value-enhancing manner. For high water-containing biomass, hydrothermal processes (HTP) are particularly promising as they require wet conditions for optimal processing anyway. In Germany, however, HTP have not yet reached the industrial level, although suitable substrates are available and technological progress has been made in previous years. This study aims to determine why this is by identifying key factors that need to occur HTP development in Germany until 2030. By using results of previous analyses within this context (i.e., literature review, SWOT analysis, expert survey, and focus group workshop) and combining them with the results of an expert workshop and Delphi-survey executed during this analysis, a comprehensive information basis on important development factors is created. Fuzzy logic is used to analyze these factors in terms of interconnections, relevance, and probability of occurrence by 2030. The results show that technological factors, such as a cost-efficient process water treatment and increased system integration of HTP into bio-waste and wastewater treatment plants, are given high relevance and probability of occurrence. The adaptation of the legal framework, for example, the approval of end products from HTP as standard fuels, has very high relevance but such adaptions are considered relatively unlikely.

Keywords: hydrothermal processes; Germany; fuzzy Delphi method; fuzzy logic cognitive map

1. Introduction

The German government has set a target of reducing the country's annual greenhouse gas emissions (GHG) by 50% in 2030 compared to the 1990 level [1]. To achieve this goal, it is necessary to use scarce resources more sustainably, which also includes a more efficient use of biogenic residues. However, currently, considerable amounts of biogenic residues and waste are being inefficiently used or not used in Europe [2,3]. The treatment of wet and sludgy biomass is particularly challenging, as it requires energy- and cost-intensive pre-treatment processes (e.g., drying, thickening, sanitization) to become suitable for conventional biomass treatment paths (e.g., pyrolysis) [4]. However, to enhance resource efficiency by sustainably utilizing residues and therefore, fostering progress towards a circular and bio-based economy, it is worth striving for value-added use of such materials. This could also reduce costs (e.g., for more expensive primary materials) and GHG (e.g., by substituting the energetic use of fossil resources), save scarce natural resources (e.g., by recycling of nutrients like phosphorus out of the residual flows) and thus promote climate protection [5–8].

For the last few years, hydrothermal processes (HTP) have gained attention as promising technologies to manage wet biomass. HTP transform wet substrates into gaseous, liquid, or solid high carbon and energy containing products via thermochemical conversion. The products can be used for several purposes, like direct use for energy production or as an intermediate for producing agricultural and pharmaceutical chemicals [4,9,10]. For optimal operation, HTP need high water containing substrates, which is why residues like sewage sludge and animal excreta are particularly suitable [9,11].

Depending on the operational conditions, different HTP types occur. At temperatures between 160 and 250 °C, pressure conditions between 10 to 30 bar, and a residence time between 1 to 72 h, hydrothermal carbonization (HTC) takes place. HTC is a coalification process that converts biomass into hydro-char [12] to be used for energetic purposes, material applications, and as fertilizer or soil conditioner [13]. At slightly higher temperatures (180 to 400 °C) and pressures (40 to 200 bar) but lower residence times (10 to 240 min), hydrothermal liquefaction (HTL) occurs. HTL is a process that transforms biomass into chemicals and bio-oils [14]. The products can be used for energy production and chemical industry [9]. At supercritical conditions (375 to 500 °C, 230 to 400 bar) hydrothermal gasification (HTG) takes place which usually needs less than 10 min for the reaction. Through HTG biomass is converted into gaseous materials, especially methane and hydrogen, which are used for energy and chemical industry [15].

Compared with other generally suitable biomass conversion processes (e.g., torrefaction, pyrolysis, composting), HTP have some advantages. Compared to torrefaction, for example, HTC products can achieve a higher energy density, energy yield, and combustion reactivity [16]. Additionally, HTC can provide economic advantages. For example, a comparative study of HTC, anaerobic digestion, and composting on the conversion of food waste showed that HTC performs economically best due to its low residence time and less substrate pre-treatment [17]. Another study showed that the HTL of algae can be advantageous compared to pyrolysis in terms of conversion yields and energy conversion rates [18].

At a first glance, HTP seem well suited to the conversion of wet biomass into high carbon and energy-containing products. Nevertheless, as a trade registry evaluation on HTP companies in Germany showed, so far, the technology has not prevailed in Germany. Based on this, since 2008, only a handful of new company foundations have been registered. This is in contrast with the general interest in these processes, which can be measured in terms of the level of research and technological progress. For example, according to a recent study, there are currently 15 patents on HTC in Germany [19]. Also, scientific interest in HTP is continuously increasing. According to Kruse and Dahmen [20], numerous published studies in Scopus since 2009 contain the keywords “supercritical gasification”, “hydrothermal liquefaction”, and “hydrothermal carbonization”. This ongoing interest indicates that there is still high potential for HTP to become an innovative biomass conversion path. This has also been confirmed by international developments. Research activities on HTP are a core issue of the Pacific Northwest National Laboratories in the U.S., where some pilot plants are also in operation [21–23]. In addition, TerraNova Energy operates a larger HTC plant in China [24] and Ingelia in Spain [25].

Also, key metrics on HTP (e.g., the higher heating value (HHV) of products, the energy and mass balance of processes, the carbon efficiency, and the specific investment and operating costs) indicate that there is potential for HTP to be further developed at a large scale. For example, the HHV of hydro-coal ranges from 24 MJ/kg (median) to 26 MJ/kg (maxima) [25–27]. In terms of the energy efficiency of HTC (including all energetic losses during the process and without a utilization step) there is also high variation—between 62 per cent (median) and 77 per cent (maximum) [28–30].

However, optimization of the technological, economic, and ecological features of HTP depends on many parameters, such as heat recovery, applied catalysts, substrates used and their moisture content, logistics as well as plant sizes [4]. An example is the connection between HTC plant sizes and investment costs based on the manufacturers’ information. The specific investment costs tend to decrease in relation to the capacity of the plants per additional ton of fresh matter biomass input (from 260 EUR/ton for 5000 tons capacity up to 50 EUR/ton for 80,000 tons capacity) [31–34]. So, economies of scale can be already observed. Further, learning curve and scale effects through more experience in the operation of plants on an industrial scale are crucial to achieving gradual optimization of essential parameters. Finally, if the parameters can be optimized, HTP will provide several advantages. For example, the HHVs of the final products are generally higher than those of fossil reference systems [4]. Greenhouse gas savings compared to fossil references may also be significant, depending on the substrate used, the energy balance, and the subsequent product use [4].

So far, only a few studies have provided information on the future development of HTP in Germany and Europe as well as the corresponding key factors. A study of the German National Academy of Science and Engineering analyzed the potential system contributions of HTC and HTL to the flexibility of a renewable energy system until 2023 in Germany [35]. It was identified that the approval of HTC coal as a standard fuel and a corresponding fuel standard are of high importance. Furthermore, they recommended the promotion of nutrient recycling and the development of a cost-effective process water treatment procedure. They suggested the use of hydro-coal as an energy carrier, soil additive, and industrial carbon carrier. For HTL it is considered critical that in Germany, algae, which is a particularly suitable substrate, is largely missing. Nevertheless, they recommend the support of nutrient recycling and the increase in quality of the liquid product [35]. De Mena Pardo et al. [19] outlined the necessary factors for the establishment of HTC at the European level, such as the abolition of the waste status of HTC products from waste biomass. They predicted that hydro-coal will first become established on the energy markets and, in the long term, will also occupy material markets. In terms of establishment in the energy sector, however, the "end of the waste" characterization is crucial. Another recent paper [20] identified the integration of HTP into bio-refineries as important future development strategy to generate synergies. Furthermore, the whole value-chain must be addressed, also including stakeholders who have so far only been marginally involved, like farmers. In a previous paper, we used a SWOT analysis to identify the most important current barriers and possibilities for HTP in Germany [36]. The results indicated that the technological readiness of the plant, including the presence of high energy and material efficiency as well as the presence of a suitable process water treatment procedure are factors of high importance. In addition, the overall costs for producing the end-product and the competitive nature of sales markets are seen as important threats. Also, the GHG are of high relevance throughout the process and can be primarily viewed as an opportunity if HTP can mobilize their potential for emission savings as compared with fossil reference systems.

However, although HTP has some promising features as a resource efficient conversion technology for wet biomass, no scaling-up is happening in Germany. Thus, this study aims to identify and prioritize key development factors for HTP that should occur in Germany by 2030 and points out their interconnections using a structured expert participation process. Furthermore, the probability of occurrence of these factors is estimated. This study also aims to provide important information on barriers that must be dealt with to allow HTP to contribute to climate and resource protection in the future.

Specifically, we used the Fuzzy Delphi Method (FDM) and Fuzzy Cognitive Mapping (FCM) in this study. The Delphi method is a forecasting procedure based on the opinions of anonymous experts collected through a multi-stage survey process. It aims to systematically foster expert consensus about uncertain developments [37]. A Delphi survey consists of several rounds of interviews. The first round usually asks for the assessment of uncertain factors and events. The following rounds then ask the experts to revise or confirm their assessments based on the results of the previous rounds [38]. As this method contains some disadvantages (e.g., relatively low consistency of expert opinions, high enforcing effort, and sometimes modifications to individual opinions in order to reach consistent total opinions), we expanded it by using the Fuzzy Delphi Method (FDM) for the final evaluation. With FDM, expert opinions are integrated with fuzzy numbers based on the cumulative frequency distribution and fuzzy integrals. Thus, FDM applies triangulation statistics to determine the distance between the levels of consensus within the expert panel [39]. Furthermore, the FDM needs just a small survey panel to deliver reliable results—an advantage for studies with a small number of suitable participants [40]. FCM is a model consisting of nodes that indicate the most relevant factors (in FCM the term "concepts" is used) of a decisional environment and relationships between them (arcs and edges). The analytical background of FCM is based on the structure and function of concept maps, including graph theory-based analyses of pairwise structural relationships between the model factors. It is therefore a decision-support tool which originated a combination of fuzzy logic and artificial neural network theory [41]. It aims to define the important factors relevant to a specific community and the relationships between them as well as optionally testing scenarios in which these factors are varied to see how the system might react under a set of possible conditions [42]. An adjacency matrix A represents the interconnections between model factors. On that basis, the number and directions of edge relations are transformed into quantitative values between −1 (inhibitory effect) and +1 (positive effect) [43]. In particular, FCM can be used to model complex systems with high uncertainty and less available empirical data [44], which, based on our experiences within this working field, is the case for this study's topic.

2. Materials and Methods

The key factors were primarily developed based on qualitative and quantitative expert evaluations and information from relevant literature. Figure 1 gives an overview of the study design.

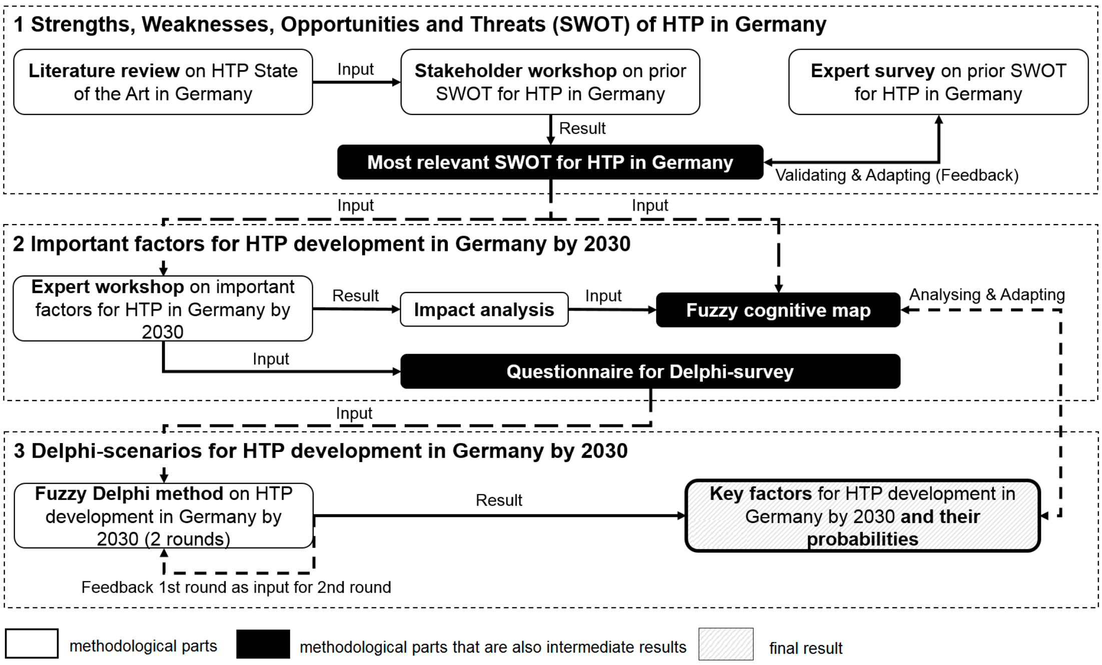

Figure 1. Study design.

The methodological framework is, in part, similar to the Hybrid Delphi method [45]. However, it also includes further methodological elements (literature review, impact analysis, fuzzy logic). Based on a comprehensive literature study [4], a moderated focus group workshop on the success and risk factors of HTP development in Germany was carried out. The results were validated and underpinned by a subsequent expert survey. A total of 41 experts, primarily scientists, plant manufacturers and plant operators from Germany and Switzerland, participated in the workshop. The expert survey panel consisted of feedstock suppliers, technology developers, technology users, retailers, product users, policy makers, and researchers from Germany. Within the workshop, the experts were asked about certain success and risk factors for HTP in Germany that were then collected, categorized, and discussed. In a subsequent expert survey, the results of the workshop were further validated by asking about the strengths, weaknesses, opportunities, and threats for HTP development in Germany. For the detailed procedure and the results of the SWOT analysis, see [36].

Based on these initial findings, a "long list" of important factors of HTP future development, their relationships, and interactions was derived through an expert scenario workshop. Six HTP researchers from the German Biomass Research Centre (DBFZ) participated. The influence analysis performed in this step served as the basis for the development of a Fuzzy-logic Cognitive Map (FCM), which provides an overview of all identified factors/concepts and their relationships. To construct the FCM, however, further expert feedback from the surveys and information from the literature review were included. In this analysis, we used multiple-valued logic scalar numbers from the discrete set $\{-1; -0.5; 0; +0.5; +1\}$ to determine the impact relations (arcs and edges) between FCM nodes (concepts). The open source web-based application Mental Modeler was used to create the FCM and identify the factors/concepts importance and connectedness [46].

Based on the results of the expert workshop and the FCM, a questionnaire for a Delphi survey was compiled and sent to 51 HTP experts via an online survey. The FCM factors/concepts (Appendix A, Table A1) served as essential inputs for the preparation of the Delphi questionnaire. However, the use of too many survey items makes cognitive assessments more difficult and thus tends to reduce the reliability of the results, which is why it was decided to integrate particularly factors/concepts with a high FCM centrality (cf. Table 1) into the survey. Nevertheless, following feedback received during the first round of interviews, several items were added to the second questionnaire.

The survey participants were selected based on their expertise. Selection criteria were as follows: (1) academic or professional recommendations, (2) well-known authors of relevant publications on the specific subject, (3) stakeholder group representative, and (4) estimated professional experience within the working field. These criteria were selected based on the suggestion by Stevenson [47] and Hasson et al. [48] to mainly include experts in the field of study (indicated through criteria 1, 2 and 4) as well as different stakeholders (criterion 3). The international participants were asked about developments of HTP in the European context, since they were assumed to have, at best, limited knowledge on the German situation. However, both the German and the European situations are comparable. Figure 2 gives an overview of the composition of the participants, their expertise, and the nations represented in the first round of interviews. The relative distribution in the second round of the survey (n = 12) was very similar.

Two rounds were conducted in this study. Twenty-seven experts participated in the first round (response rate 1st round: 53%). Of these 27 people, twelve participated in the second round (response rate 2nd round: 44%). The following item-categories were part of the survey (assessment scales are explained in the Appendix B, Table A2): (1) relevance of factors for HTP development in Germany by 2030, (2) relevance of risks for HTP development in Germany by 2030, (3) estimated probabilities of factor occurrence by 2030 and (4) certainty in assessing per item-category.

Besides evaluating with scales, the experts had the opportunity to explain their selection and assessment in text fields. For both rounds, 22 comments on capacity development, five comments on success factors, four notices regarding risks, and eleven notes on the development of biomass utilization rates were provided. By means of qualitative content analysis (i.e., differentiation between pros and cons, frequencies of keywords, identification of consensus statements) essential statements were summarized (Appendix C, Table A3). The hints of the first round were also included in the preparation of the questionnaire for the second round.

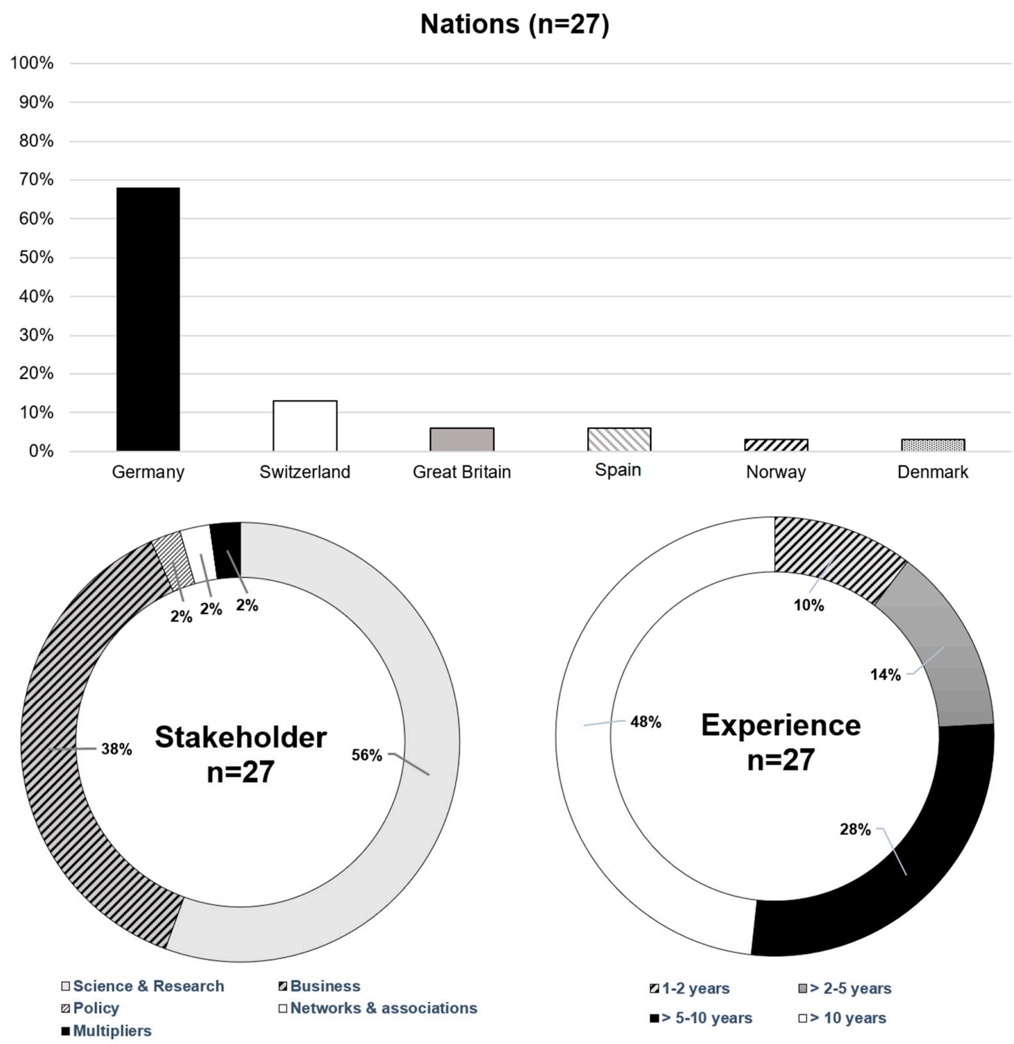

Figure 2. Participants of the first Delphi-survey round.

After the first round, an interim evaluation took place, which showed the degree of agreement in the expert assessments and the frequency of distributions of the first tendencies by descriptive statistics (median, standard deviation, interquartile range (IQR)). The questionnaire for the second round of the survey was adjusted, taking into account the results from round 1. After executing the Delphi survey, we analyzed the results by using the FDM which consists of the following steps [49]:

1. Determining experts (see previous explanations).
2. Selecting a linguistic scale to be converted into a fuzzy-scale (cf. Appendix B, Table A2).
3. Calculating the difference between the average fuzzy number (m) and each experts' fuzzy number (n) per item by using following formula:

$$d\ (\widetilde{m},\ \widetilde{n}) = \sqrt{\frac{1}{3}\left[(m1-n1)^2+(m2-n2)^2+(m3-n3)^2\right]} \quad (1)$$

4. Determining the threshold value for consensus/dissent of the expert panel:

In accordance with [38], we chose a threshold of $d \leq 0.2$ to make a decision as to whether the experts had reached consensus on the item. Next to this, the frequency of expert agreement is presented as the percentage of $d \leq 0.2$ per item-category in relation to all items. A value of $\leq$75% represents panel consensus.

5. Defuzzification:

To determine a ranking of the most relevant/probable factors per item-category, it is necessary to defuzzify the fuzzy values into a crisp-value (A_i). For this, we used the following formula in accordance with [38]:

$$A_i = \frac{1}{3}(m1 + m2 + m3) \quad (2)$$

3. Results

3.1. Factors for HTP Development in Germany by 2030 and Their Relations

The development factors and risks were primarily derived on the basis of the expert workshop and the aforementioned previous SWOT analysis executed by the authors [36]. Above all, the expert workshop served as the basis for identifying areas of interest. The factors were then further differentiated and backed up with information from the literature. The whole list of factors is part of the appendix (Table A1).

The factors were assessed in the expert scenario workshop by means of an impact matrix with regard to their mutual influences. Based on this, a Fuzzy-logic Cognitive Map (FCM) was constructed. Figure 3 shows a part of the overall FCM for the relationships of the factor "Regular Fuel Recognition".

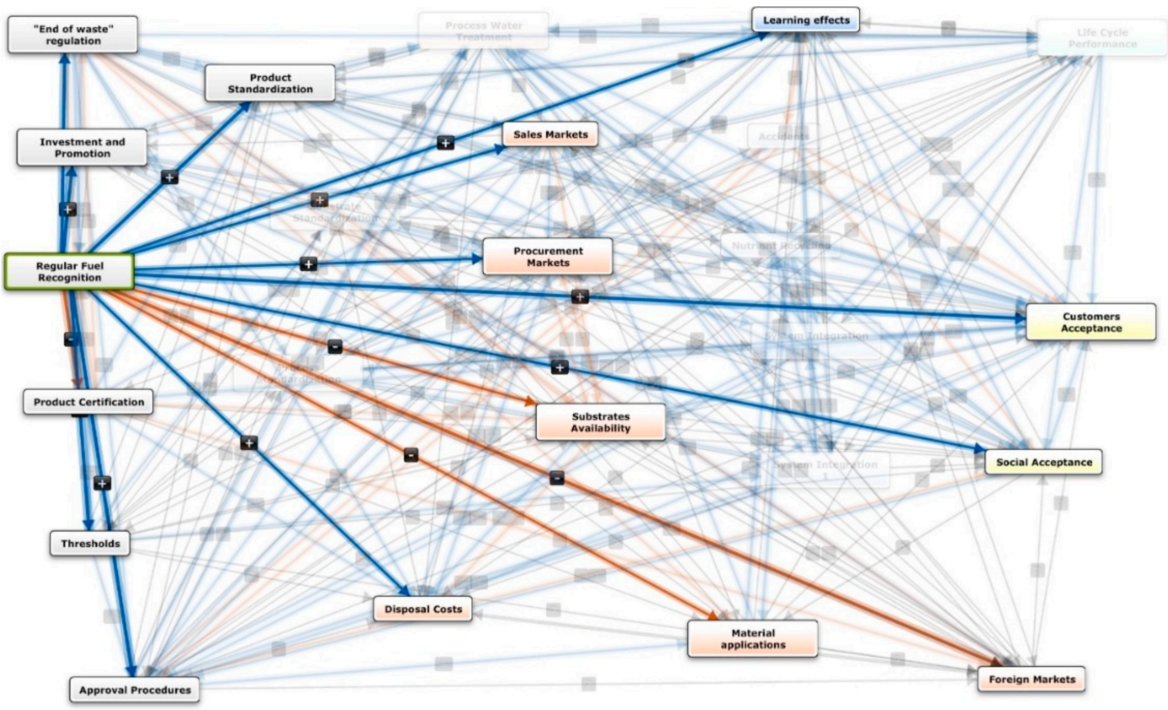

Figure 3. Part of the Fuzzy-logic Cognitive Map (FCM) for the impact of the concept "Regular Fuel Recognition" on other system concepts (expert knowledge-based FCM created with the Mental Modeler).

Since FCM is based on graph theory, which provides a wide variety of indices, we can also make statements about the structure of the system as well as gain information about the functions of individual factors. Table 1 lists the most relevant metrics for the developed FCM including a short definition of the indices.

Table 1. FCM indices and their scores in the hydrothermal processes (HTP) model.

FCM Indices	Explanation	Indices in HTP Model
N (concepts)	Indicates the total number of system factors [50,51].	24
N (connections)	Indicates the total number of connections between the system concepts [50,51].	235
N (transmitters)	Indicates the total number of concepts that influence other concepts but are not affected by other concepts [50,52].	0
N (receiver)	Indicates the total number of concepts that are influenced by other concepts but have no effect on them [50,52].	1
N (ordinary)	Indicates the total number of concepts that affect and are affected by other concepts [50,52].	23
Density	This index shows the networking degree of the system, i.e., the number of concepts and edge relations. A high density indicates that several probable management options exist [50,52]. The density can have a value between 0 and 1.	0.43
C/N	The number of connections divided by the number of concepts. A low C/N score indicates a high degree of system connectedness [50,51]. Low is relative in this context, because it must be seen in context with other comparable systems.	9.79
Outdegree & Indegree	Information about the concept degree as a transmitter (driver), receiver (output), or force that conveys effects (ordinary) [53].	Highest Outdegree (highest driving force): Regular Fuel Recognition (11.5)
		Highest Indegree (highest receiving force): Customer Acceptance (10)
Centrality	Indicates how strongly a concept influences the whole system [53,54].	Highest Centrality: Regular Fuel Recognition (13.5)
Complexity	Illustrates the degree of model accuracy and measures the degree to which outcomes of driving forces are considered [50,51].	Infinite

3.2. Results of the Fuzzy-Delphi Method

Table 2 summarizes the results of consensus or dissent after the second round. For this purpose, the determined fuzzy values (d) are given, where $d \leq 0.2$ is the threshold value. Grey shaded values are the factors where consensus was reached. In addition, the percentage of expert consensus is specified. This indicates how many item evaluations of the entire panel in relation to the total items did not exceed the threshold. Here, a value of at least 75% is the consensus criterion.

Table 2. Results on the fuzzy evaluation regarding expert consensus/dissent after round 2.

No.	Thematic Category	Consensus/Dissent after Round 2 (n = 12)		
		d_{factor}	d_{risk}	$d_{probability}$
Political-legal factors				
1	Regular fuel recognition	0.178	0.183	0.204
2	Investment and promotion	0.277	0.241	0.136
3	"End of waste" regulation	0.170	0.221	0.263
4	Product certification	0.153	0.221	0.164
5	Thresholds	0.300	0.239	0.288
6	Approval procedures	0.267	0.239	0.236
7	Product standardization	0.204	0.170	0.136
8	Substrate standardization	0.159	-	0.192
9	Process standardization	0.083	0.265	0.213
Economic factors				
10	Sales markets	0.187	0.085	0.181
11	Procurement markets	0.209	0.170	-
12	Substrate availability	0.187	0.186	0.166
13	Disposal costs	0.209	0.293	0.199
14	Material applications	0.226	-	0.235
15	Foreign markets	-	0.208	-
Technological factors				
16	Process water treatment	0.170	0.204	0.136
17	System integration 1	0.115	-	0.162
18	System integration 2	0.229	-	0.187
19	Nutrient recycling	0.178	-	0.236
20	Learning effects	0.200	0.140	0.200
21	Accidents	-	0.265	-
Ecological factor				
22	Life cycle performance	0.378	-	-
Mean d_i		**0.207**	**0.205**	**0.193**
Percentage of expert consensus		**72%**	**71%**	**76%**

Table 2 shows that after the second survey round, majority consensus was achieved in at least one item-category (factors, risks, probabilities). However, for thresholds, approval procedures, material applications, foreign markets, accidents, and life cycle performance, no consensus was reached at all. The panel consensus (last row of Table 2) was not reached regarding factors and risks (<75%), which likely shows that the expert assessments tended to be furthest apart for these item-categories.

However, compared to the first round, the second round showed a significant increase in expert consensus. The expert consensus rate increased by 28 percentage points in the assessment of the relevance of the factors, by 19 percentage points in the assessment of the relevance of the risks, and even, by 33 percentage points in the probability of occurrence estimates between the rounds. For some items, there were considerable differences. In particular, the relevance of process standards showed a very strong difference between rounds 1 and 2 ($\Delta d_{factor} = -80\%$). This could be due to the fact that in the second round, experts who regard process standards as equally relevant in particular were still involved. This reveals one of the weaknesses of the Delphi method, as there is sometimes a high drop-out rate (in this case 56%) between the rounds that can cause changes in the results due to differences in the survey panel, rather than solely due to adjustments based on the previous round's results. However, one basic assumption of the Delphi method is that expert consensus increases due to the adaption of evaluation based on the previous round's results, which is why we basically also assumed this for the consensus increase in this study. For the factors/concepts in which a consensus was reached (grey shaded in Table 2), Table 3 shows the values (A_i) after defuzzification. Based on this, the items' fuzzy logic-based relevance/probability can be ranked. Factors/concepts that are not greyed out in Table 3 were no longer considered in the corresponding categories, as a dissent prevailed in the expert assessments. We differentiated between:

- A_f = defuzzified value for factors
- A_r = defuzzified value for risks
- A_p = defuzzified value for probabilities
- A_c = defuzzified value for certainty in assessment
- $Rank_f$ = Rank in relation to other factors
- $Rank_r$ = Rank in relation to other risks
- $Rank_p$ = Rank in relation to other probabilities

Table 3. Ranking of consensus items in terms of relevance and probabilities after defuzzification.

No.	Factors with Consensus in at Least One Item-Category	A_f	$Rank_f$	A_r	$Rank_r$	A_p	$Rank_p$
Political-legal factors							
1	Regular fuel recognition	8.2	3	5.8	2	n.c.	n.c.
2	Investment and promotion	n.c.	n.c.	n.c.	n.c.	2.9	9
3	"End of waste" regulation	8.6	2	n.c.	n.c.	n.c.	n.c.
4	Product certification	7.4	5	n.c.	n.c.	3.8	8
7	Product standardization	n.c.	n.c.	5.6	3	3.9	7
8	Substrate standardization	2.6	10	-	-	2.0	10
9	Process standardization	2.8	9	n.c.	n.c.	n.c.	n.c.
Economic factors							
10	Sales markets	4.6	8	2.8	5	6.1	4
11	Procurement markets	n.c.	n.c.	4.4	4	-	-
12	Substrate availability	5.0	7	2.8	5	6.8	1
13	Disposal costs	n.c.	n.c.	n.c.	n.c.	6.2	3
Technological factors							
16	Process water treatment	8.0	4	n.c.	n.c.	6.8	1
17	System integration 1	9.0	1	-	-	6.0	5
18	System integration 2	n.c.	n.c.	-	-	4.6	6
19	Nutrient recycling	8.2	3	-	-	n.c.	n.c.
20	Learning effects	6.4	6	7.4	1	6.4	2
Certainty in the assessment of the item category according to the experts' own statements: A_c		6.4		5.6		5.0	

"n.c." = no consensus reached; "-" = factor was not part of this item-category.

Table 3 shows that the assessments of the relevance of occurrence of a factor (A_f) and the risk of non-occurrence (A_r) are very different. For example, the absence of learning effects (e.g., lack of reference facilities) is considered to be a significant risk (7.4). However, the relevance of this factor is also still high (6.4) but only in the midfield relative to other factors. The uncertainty according to the panelists' own assessments (A_c) is highest in the probabilities and lowest in the relevance of the factors. However, the values are close to each other, which is why the assessment certainty of the item categories is largely the same.

Regarding the relationships between mutually relevant factors and corresponding probabilities (grey shaded in Table 3), only a few factors show high values (i.e., near to 10) for both. Figure 4 visualizes the relationships.

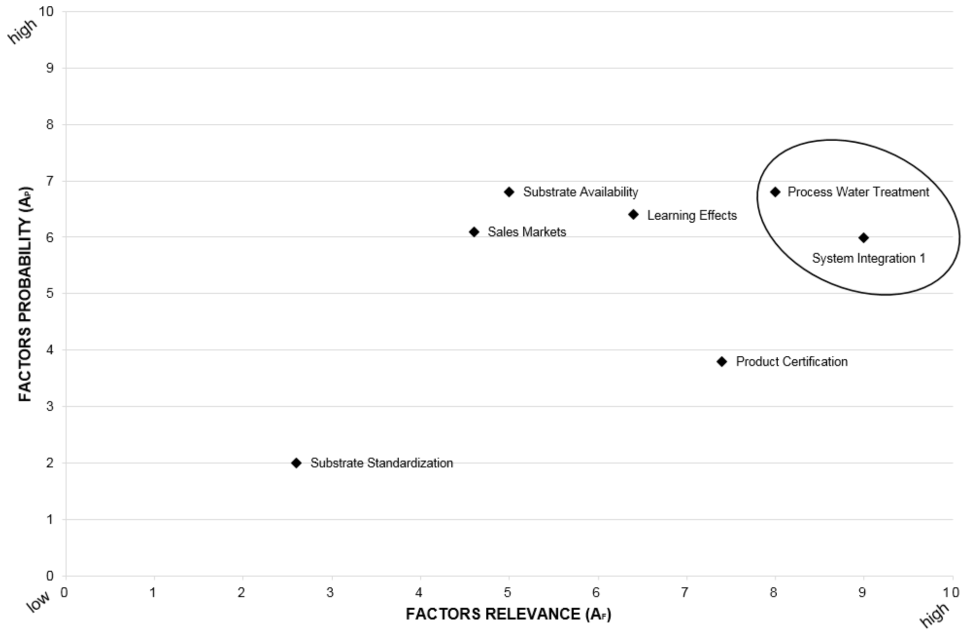

Figure 4. Combination of relevance and probability of consensus factors after defuzzification.

Only two factors were considered to be highly relevant and also highly probable. Namely, the introduction of a cost-effective process water treatment and the integration of HTP into existing bio-waste and wastewater treatment plants.

4. Discussion

Although HTP has already been shown to have an advantage on some points (e.g., HHV, energy yields, decreasing specific investment costs while increasing capacity), the analysis showed that there are several factors related to the development of HTP in Germany that have hindered successful development so far. Above all, political-legal aspects are strongly inhibiting a scale-up in Germany, but adaptions in the near future are considered unlikely. This shows that the experts involved think that the legislator or the political decision-makers have relatively little ambition to promote the development of HTP more strongly. This is already evident today as some German HTP plant manufacturers and operators are already focusing on foreign markets (especially China). Nevertheless, HTP could considerably contribute to the achievement of a bio-based economy by efficiently converting currently difficult-to-use wet biomasses into valuable products. However, the adaptation of the legal framework is urgently needed for this. If the national legislator does not take action, an important step could also be the development of an EU regulation on the end-of-waste status of waste biomass products, similar to those already introduced for scrap iron, scrap steel, and scrap aluminum as well as for certain types of glass. One of the reasons for this is that the legal uncertainty for plant operators and product users is very high, which, in turn, increases transaction costs [55]. Due to the fact that HTP products cannot be used as standard fuels, the energy market cannot be fully penetrated, which significantly reduces the product's market potential. However, there are still many problems at the technological level. So far, Germany is still a technology leader in the field of HTP (e.g., as indicated through patents) [19]. Based on results of this analysis, it is politically recommendable to work actively on measures that ensure that HTP are used economically in Germany and do not become exclusively an export product as this could cause related companies to relocate their headquarters abroad.

In addition, technological advancements are considered to be relevant drivers and are also estimated to be relatively likely. Above all, a mature technology for the cost-effective treatment of the process water is urgently needed to reduce the overall related costs and thus increase the cost-effectiveness of the process. In addition, an efficient treatment process for polluted water is also needed to aid in environmental protection. Potential for promoting the development of HTP is seen particularly in system integration, for example, into existing bio-waste and waste-water treatment plants (WWTP). The resulting synergies can, in particular, save logistics costs and directly link the locations of substrate occurrence, conversion technology and, in some cases, customers. The experts probably regard technological advances as likely because corresponding research and development is very active. In particular, cost-effective solutions for the process water treatment are being intensively researched [56–58], which is why suitable solutions are likely to be expected in this area in the foreseeable future. As an overview, Table 4 summarizes the main results of this study, i.e., the most crucial barriers and potential for future HTP development and the spread of technology as well as suggestions for possible measures to reach the potential benefits for HTP and reduce the barriers to achieving these.

Table 4. Consensual key potential benefits and barriers for HTP development in Germany by 2030 and potential measures.

Key Development Factor(s)	Potential Measure(s) to Reach Potential Benefits or Reduce Barriers
Key potentials	
Political-legal	
An end-of-waste regulation is being introduced for HTP products (i.e., products from bio-waste, sewage sludge etc.), and HTP energetic products (e.g., hydro-coal) are recognized as standard fuels.	The European or national legislation has to be adjusted accordingly. This means that a regulation must be introduced that allows the energetic use of products from waste biomass. Such a regulation could be very similar to regulations already being introduced for broken glass and steel scrap.
Technological	
Integration of HTP into existing bio-waste treatment plants and waste-water treatment plants (WWTP) including nutrient recycling	Research on suitable technological solutions for the most efficient integration of HTP into such plants must be fostered. Concepts from biorefinery research could possibly be used as a basis for good solutions. However, relevant stakeholders, especially plant operators, must be closely involved (e.g., with common workshops) to reduce reservations and develop good concepts together. An important issue for bio-waste plant operators and WWTP operators could be nutrient recycling as this would provide an additional economic product (next to HTP products itself), which is highly demanded (esp. phosphorus [59])
Key barriers	
Political-legal	
Unambitious politics and obstructive legislation, i.e., no introduction of "end of waste" directive or alternative (e.g., product certification).	Relevant political decision-makers have to be motivated for legislative action. Scientifically-based policy advise (e.g., Scientific Advisory Boards) could be an important instrument to motivate decision-makers. To create a suitable argumentative basis for this, research on the economic and ecological benefits of HTP is necessary but must also be translated into easily understandable messages and communicated most efficiently. Next to this, political decision-makers must be integrated into several activities on HTP to increase attention on the technology. Best-practice cases (business cases) could also be useful to show the functioning and advantages of the technology.
Technological	
The understanding and knowledge of the process will not increase considerably (missing learning effects, for example, through missing reference systems/business cases).	To reduce this barrier, investment and promotion activities are especially important (e.g., by public or private funders and investors). Through this, larger pilot and demonstration plants can also be developed which may help to increase the understanding of the processes on larger scales. Such reference plants are important to give investors an impression of how the technology works, which, in turn, could generate further investments. Learning effects will occur if sufficient experience with the operation of larger plants is made. Business cases can serve as important information basis for new projects.

As mentioned in the introduction, few studies have focused on this issue so far. However, the results of this study are in line with the findings of the similar ones (e.g., the importance of having an efficient process water treatment procedure and the approval of HTP products from residues and waste as standard fuels) which confirms the high importance of the identified key factors. The novel aspect of this study, however, is that in addition to the relevant literature, extensive expert knowledge was included and evaluated in a structured manner. In addition, this study initially depicted all relevant key factors and did not focus on selected aspects directly at the start of the analysis, which is why the methodology can be regarded as non-normative. The application of FCM shows, for the first time, how the individual factors are related. The use of fuzzy logic also takes into account the bias of qualitative assessments (e.g., due to different participants' estimations of "important" and "unimportant"). Although the studies mentioned in the introduction showed very similar results to this analysis, some only considered individual technologies and not the entire technology platform (e.g., [19]) or they focused on very specific contexts (e.g., the contribution of HTC and HTL to the flexibility of a renewable energy system) (e.g., [35]), which is why not all relevant system factors were considered. The aforementioned studies did not prioritize the potential benefits and barriers to HTP development like this analysis, but they also classified them into categories and highlighted the high importance of the already mentioned legal and technological factors. Hence, this study confirms the entirety of the results of the mentioned studies and substantiates them both in terms of content (expert knowledge) and by using an alternative methodology (fuzzy logic).

The applied methodology to derive particularly relevant factors, risks, and probabilities of occurrence is unique in this form. Although other technology assessments have applied the Fuzzy Delphi method [60], Fuzzy-logic Cognitive Mapping [61], or SWOT analysis [62], they did not use such a combination. The advantage of this method is the versatile participation format that greatly increases the objectivity of the results overall, since several correction and feedback loops are part of it. The combination of workshops and surveys within this study makes it possible for both conduction of the discourse (workshops) and collection of anonymized content (Delphi survey) to occur. Although other comparable studies also applied participation as a qualitative methodological element [63], the particular kind of methodological combination used (cf. Figure 1) has not previously been used in the literature. The core of information filtering into relevant and probable factors is the Fuzzy Delphi Method. With a total of 27 experts from different stakeholder groups in the first round, this Delphi survey achieved a high level of representativeness, since there are very few HTP experts in the study area anyway. The number of participants is an extremely important factor in achieving meaningful results, so it is strongly recommended that experts are already mobilized before a study of this type is begun. Through the use of fuzzy logic, it became possible to bypass some disadvantages of the classical Delphi method. In particular, the different types of assessment by people on the basis of linguistic scales can be easily circumvented by fuzzy scales [64]. Another key element of this analysis was the application of the FCM method. Again, fuzzy logic was used to translate qualitative expert assessments into a model that represented the overall system of factors. In this study, the mapping was conducted as part of a workshop with six experts. We preferred a smaller group to ensure discussion and to prevent over-standardization of the workshop. A standardization of the mapping, for example, via online formats or targeted queries, would certainly allow a larger number of participants. The creation of an FCM requires a high level of cognitive performance, but it helps to structure the complexity of a system to identify feedback loops or so-called "hidden patterns". Identification of the dependencies of the factors must be carried out carefully, as this is the central way for the system effect to be identified. Nevertheless, the results are meaningful as a "scoreboard" and do not guarantee objective accuracy, as this is not the aim of a qualitative analysis like this one anyway. Looking into the future always involves high uncertainty and particularly shows ranges and opportunities.

5. Conclusions

In this study, we asked for the reasons why HTP does not yet prevail on a large industrial scale in Germany. By means of a literature- and expert knowledge-based fuzzy logic analysis, we identified key factors and prioritized them. The study results show that political and legal adjustments to the relevant framework conditions as well as technological improvements are seen as very important for the positive future development of HTP in Germany. This especially includes the key potential benefits shown in Table 4. These factors are strongly connected to other system components which shows their high impact on the whole system. The results can serve as important information for

HTP stakeholders in Germany, especially political decision-makers, entrepreneurs, and researchers. However, the limitations of the study are that the findings are only valid for the German situation. Other nations require their own comparative studies. Additionally, the study was highly qualitative in nature due to the insufficient information and data situation in this field of research. Hence, some uncertainty remains which is, nevertheless, very common for analyses that deal with future developments. In the future, the identified factors and interconnections shall serve as a basis for upcoming scenario case studies focusing on the system and plant levels (also, in part, quantitively). In this way, we hope to gain even more insight into desirable technological, economic, ecological, and political-legal developments for HTP by 2030 in Germany.

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Appendix A. List of Relevant System Factors for HTP Development in Germany

The factors are formulated in positive form and thus represent a desired event; the corresponding negative formulation represents a risk. However, the non-occurrence of a factor is not always considered as a risk. In addition, risks were identified that do not necessarily represent a development factor in their inverse effect (accordingly, they are not formulated in positive form). Such factors are marked with asterisks.

Table A1. "Long list" of factors for HTP development in Germany by 2030.

x_i	Tagging	Factors/Concepts Explanation
Political-legal factors/concepts		
1	Regular fuel recognition	HTP energetic products (e.g., hydro-coal) are recognized as standard fuels. This factor is strongly connected to the fourth factor as this represents an alternative requirement for the recognition of HTP products as standard fuels.
2	Investment and promotion	Investment incentives (e.g., policy support instruments) and/or technology and research funding programs for HTP are being introduced or, rather, promoted.
3	"End of waste" regulation	An end-of-waste regulation is being introduced for HTP products (i.e., products from bio-waste, compost, etc.). Comparable regulations already exist for broken glass and steel scrap.
4	Product certification	Official recognition certificates for HTP products are introduced and issued accordingly by the competent authorities. This helps to reduce uncertainty in practice in terms of the classification of HTP products as fuels.
5	Thresholds	Thresholds relevant to HTP (e.g., the Federal Immission Control Act) are relaxed as far as reasonably possible.
6	Approval procedures	Approval procedures for new HTP plants are accelerated which might save costs during the planning and construction phase.
7	Product standardization	The quality of HTP products is standardized (e.g., fuel standard). This helps to reduce uncertainties with HTP products and sales markets (e.g., for product users) and enhances transparency.
8	Substrate standardization *	The quality of HTP substrates is standardized (e.g., ISO standard). This helps to reduce uncertainties with HTP procurement markets (e.g., for substrate users) and enhances transparency.
9	Process standardization	Process standards are introduced (e.g., ISO standard). This helps to reduce uncertainties for plant constructers and operators and enhances transparency.

Table A1. *Cont.*

x_i	Tagging	Factors/Concepts Explanation
Economic factors/concepts		
10	Sales markets	The competition on HTP relevant sales and product markets (e.g., energy carriers, fertilizers, substitutes for chemical products) decreases. Thus, the relative market share for HTP firms might be increased.
11	Procurement markets	The competition in HTP relevant procurement markets (e.g., animal excreta, sewage sludge) decreases. Thus, more usable substrates for HTP might be available, possibly near to the plant location.
12	Substrate availability	The available and technically usable amount of substrates increases. Thus, in centralized concepts, plants might be able to handle higher capacities, or in decentralized concepts, more substrates will be available near to the plant location assuming that substrate availability increases equally in Germany.
13	Disposal costs	Disposal costs for HTP substrates per mass unit (e.g., ton) are increasing. Thus, revenue for the disposal of such substrates might also increase which would generate additional income for HTP plant operators.
14	Material applications *	HTP products are primarily used for material applications (e.g., as fertilizer, functional carbon). This could result if energy markets remain unprofitable due to legal barriers (missing recognition as regular fuels). Products for HTP might be primary applied in markets for bio-based products. However, this factor strongly depends on missing legal adjustments regarding fuel recognition according to experts' opinions.
15	Foreign markets **	HTP plant manufacturers and operators concentrate almost exclusively on foreign markets. This might be a result of missing market demand, an insufficient or rather braking legal framework, low relative market shares for HTP products in related markets or missing political incentives and willingness to promote HTP in Germany.
Technological factors/concepts		
16	Process water treatment	A cost-efficient and sustainable solution for process water treatment is being developed and applied nationwide. This might promote the overall economic (and ecological) performance of HTP as the process water treatment is currently also a relevant cost (economic) factor that might make HTP concepts uneconomic.
17	System integration 1 *	HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities. Thus, the locations of substrate occurrence and treatment facilities could be integrated optimally, leading to lower logistic costs. Also, other synergies might be generated, e.g., process water is treated directly by the wastewater treatment plant on site.
18	System integration 2 *	HTP are increasingly being integrated into bio-refineries. This could also generate considerable synergies (e.g., cascade usage networks).
19	Nutrient recycling *	The nutrient recovery is enhanced. Especially, nutrient recovery from the process water might be promising as the process water must be treated anyway. Due to political and legal frameworks (2017 amendment of sewage sludge ordinance) that especially require phosphorus recovery from sewage sludge, this might be a useful strategy.
20	Learning effects	The process understanding and knowledge increases (learning effects, for example, through reference systems/business cases). According to the learning curve effect theory, this will especially reduce the cost per unit of product which is why this is also, in part, an economic factor [65].
21	Accidents **	Accidents with existing facilities reduce trust in the safety of the technology. This might especially affect plant operators and society which is why this factor is strongly connected to social factors.
Ecological factor/concept		
22	Life cycle performance *	Research on climate and resource protection by HTP will be intensified. Results on this will also successively improve the life cycle performance due to new insights (e.g., the stability of HTC coal in the soil as CO_2 sink). This might especially promote social acceptance of the technology. However, the life cycle performance is strongly connected to several other factors (e.g., reduced pollutants in process water after treatment) which is why this factor is just one part of promoting the life cycle performance.
Social factors/concepts		
23	Customer acceptance	Customer acceptance of HTP increases. This might be the result of technological progress, legal adjustments that promote HTP, higher transparency regarding HTP product quality (e.g., end-product customers), substrate quality, and process performance (e.g., customers for facilities/plant operators).
24	Social acceptance	The social acceptance of HTP increases or rather, society regards HTP as a resource efficient technology for future biomass conversion.

* Factor is not considered as a risk if it not occurs; ** Solely represents a risk.

Appendix B. Scale Relations

Table A2. Linguistic variables of Delphi survey item-categories and corresponding Likert and fuzzy scales.

Linguistic Scale	Likert Scale	Fuzzy Scale		
For item categories "relevance of factors" and "relevance of risks"				
extremely relevant	5	0.6	0.8	1
very relevant	4	0.4	0.6	0.8
relevant	3	0.2	0.4	0.6
barely relevant	2	0	0.2	0.4
irrelevant	1	0	0	0.2
For item category "probability of factors"				
very high	5	0.6	0.8	1
high	4	0.4	0.6	0.8
middle	3	0.2	0.4	0.6
low	2	0	0.2	0.4
very low	1	0	0	0.2
For item category "assessment (un)certainty"				
very certain	5	0.6	0.8	1
certain	4	0.4	0.6	0.8
relative certain	3	0.2	0.4	0.6
uncertain	2	0	0.2	0.4
very uncertain	1	0	0	0.2

Appendix C. Expert Statements in the Delphi Survey

Table A3. Summarized comments and hint of experts in the Delphi survey.

Category	Key Statements of the Experts
Arguments for a plant capacity increase	• Capacity will increase for plants that currently only exist on a pilot scale. • Capacity expansion due to legal adjustments and additional economic opportunities (e.g., additional revenue from rising carbon allowances due to an end of waste regulation for bio-coal). • Easy scalability of the systems due to modular design. • Learning effects, experience, and technological advances (for example, process water treatment solutions). • Scale effects and scale advantages. • HTC plants must be based on wastewater treatment plants of the size 3–4, therefore requiring a capacity of 50,000 metric tons biomass input per year.
Arguments against a plant capacity increase	• For the most relevant fields of HTP application (mainly the disposal sector), the current capacity is sufficient. • For wet biomass, only relatively small amounts are meaningful for ecologic (CO_2) and economic (costs) transport, which limits the capacity. • The plants are used decentral, because substrate availability is crucial. That limits the capacity.
Notes on relevant success factors	• HTP must be evaluated holistically to show its potential benefits. • Regulatory and political measures need to be implemented.
Notes on relevant risk factors	• Today's expectations of the technology will be not fulfilled (especially economically and ecologically). • The environmental effects are misjudged. • The pressure of competition is increasing.

Table A3. *Cont.*

Category	Key Statements of the Experts
Arguments for an increase in the biomass utilization rate	• Environmental benefits compared to landfilling and anaerobic digestion promote HTP deployment, but it has to be backed by legislation and incentives. • Growing environmental awareness.
Arguments against an increase in the biomass utilization rate	• No significant technological advancements. • Municipal users do not engage in HTP. • The spatial distribution of substrates limits their efficient use.

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Paper V

The following text reassembles the full text-version of the article.

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What could be the future of hydrothermal processing wet biomass in Germany by 2030? A semi-quantitative system analysis

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A B S T R A C T

The hydrothermal conversion of wet biomass into carbon-rich products is credited with a high potential. But in Germany corresponding large scale facilities have not been established yet. In order to investigate why this is the case, we have identified key factors for the development of hydrothermal processes (HTP) in Germany in previous works. Based on this, this study presents three scenarios of HTP development in Germany by 2030 that represent different combinations of key development factors considering high probability and relevance of occurrence as well as risks in case of factors non-occurrence. Using fuzzy cognitive mapping, connections between the factors are modelled. Further, the system is analysed on its reaction to the scenarios, so that important impacts can be identified. A punctual result is, that for the scenario including most relevant key factors, a normative and economic stabilization of the system is observable. This is above all reasoned in the assumed supporting legal framework. Thus, this path is the most suitable for a successful HTP development in Germany according to this analysis.

1. Introduction

For the future establishment of a resource-efficient circular- and bioeconomy, the most efficient use of biogenic residues is of great interest [1–6]. Hydrothermal processes (HTP) are currently credited with a high potential to lead to a more efficient use of wet biomass. HTP are thermochemical processes that convert wet biomass under certain pressure and temperature conditions into bio-coal, bio-oil and biogas, which are suitable for energetic and material applications [7]. HTP are classified as shown in Table 1:

Unlike solid residues, wet biomasses require expensive pre-treatment processes (e.g., drying and thickening) before they are suitable for most biomass conversion processes [7], which is why simple and less costly treatment paths (e.g., combustion) are usually applied [16]. Regarding resource efficiency, such conversion paths are not optimal, because they do not exploit the complete energetic and material substrate potential [1].

Hence, HTP seems better suited to efficiently converting wet biomass into energy- and carbon-rich products. However, the technology has so far not been successful in Germany [17]. In a previous study [18], we identified opportunities and risks of HTP development in Germany. The benefits of HTP include the lower carbon footprint and higher energy efficiency of the processes compared to alternative methods (e.g., anaerobic digestion). Barriers arise due to a lack of experience in industrial continuous operation and constraints in the current legal framework (e.g., legal waste status of the solid product of HTC). We used these results to derive relevant key factors for HTP development in Germany until 2030 and their occurrence probabilities. Fig. 1 gives an overview of the methodological process.

The identification and categorization of the key factors was based on a SWOT analysis and expert workshop with impact analysis. From these analyses, a fuzzy cognitive map (FCM) was created (presented later in this study). Further, a Delphi survey with 51 European HTP experts was executed and evaluated using fuzzy-logic. Nevertheless, due to the qualitative nature of the methodology, uncertainties remain regarding the identified factors (e.g., regarding completeness, assessment of relevance and probability of occurrence). However, the authors' preparatory work is the only source of information of this kind; so far, no comparable research results have been available. Various feedback loops and the consistent use of information ensured that all relevant factors were identified and assessed as far as possible.

Based on the results of this process, a list of key factors for HTP

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development in Germany by 2030 resulted [17]. Table 2 summarizes the factors and provides information about the factors' estimated relevance for the future development of HTP (relevance of occurrence), risks in case of non-occurrence and probabilities of occurrence. Not all of the factors pose a development risk if they do not occur. In addition, some factors are not development drivers but rather risks. Corresponding factors are marked with asterisks and defined in the notes below the table.

Based on the information in Table 2, this work aims to map the system of factors and analyse their reaction on HTP scenarios, that are descriptions of possible future situations, combining a network of influencing factors. Scenarios depict possibilities and thus include a high degree of uncertainty in the assessment of future developments [21–24]. To illustrate the contribution of the energetic use of biomass to the renewable energy system, for example, several scenario analyses have already been conducted in Germany [25,26]. HTP has not been part of such studies. One reason is that the technology has not reached industrial maturity in Germany and therefore does not currently make any appreciable contribution to the renewable energy system. Nevertheless, a study by the German National Academy of Science and Engineering concludes that HTC and HTL could make an important contribution to the renewable energy system by 2023, closing the gap between combustion, gasification and pyrolysis and the microbiological processes [27].

Apart from the mentioned study, there is hardly any research into the future of HTP in Germany. Instead HTP research currently focuses on process optimization [28,29] and techno-economic and ecological analyses [30–32]. Predictions are therefore dependent on many uncertainties and driven by various assumptions. A trend projection based on historical data is not possible for HTP, as there are insufficient data. Nevertheless, scenarios can be useful to learn more about the overall system behaviour and important factors and patterns. Additionally, they can reveal relationships and possible developments. Hence, the results of this study can help not only to produce recommendations for decision-makers in politics, science, industry and civil society, but also to identify "hidden patterns" and self-reinforcing feedbacks in the system.

2. Materials and methods

2.1. Fuzzy cognitive maps for system modelling

The relationships and connections of the factors in Table 2 were modelled to illustrate the system relationships using FCM, which is a tool for representing the complex characteristics of non-linear dynamic systems, which may not be supported by a deterministic mathematical model [33]. Fuzzy signed graphs are used to model events and values as a collection of concepts (i.e., fuzzy sets that represent the factors), by forging a causal link between them [34,35]. Due to their flexibility, adaptability and the intuitive way they are constructed, FCMs are increasingly used in various scientific disciplines [36–38] and are an important part of soft computing research [35]. An advantage of an FCM approach over hard computing approaches (e.g., system dynamics) is that it is tolerant of imprecision, uncertainty and approximation. Soft computing approaches such as FCM are well suited to handling highly complex (non-linear, multimodal, high-dimensional, etc.), poorly structured or ill-defined problems [39].

Another reason we decided to use this approach is that other studies have used FCMs to determine future technology development or have recommended them for this purpose. For example, Amer et al. applied FCMs to determine scenarios for the wind-energy sector in Pakistan to create a technology roadmap [40]. Jetter reviewed applications of FCMs and described them as being especially suitable for scenario planning and forecasting of technology trends [41].

A standard FCM is defined by a set of functions $(X,\ W,\ C,\ f)$ [32,34]:

- $X = \{x_1, x_2, \ldots, x_n\}$, which represents the set of n concepts. They form the nodes of the graph.
- $W : (x_i, x_j) \rightarrow$ where w_{ij} is a function of $X \times X$ *to* $K \rightarrow [-1, 1]$ associating w_{ij} to a pair of concepts (x_i, x_j), with w_{ij} denoting a weight of directed edge (magnitude) from x_i *to* x_j, *if* $i \neq j$; otherwise, if w_{ij} is equal to zero, then $i = j$. Thus, $W(X \times X) = (w_{ij}) \in K^{n \times n}$ is an adjacency matrix, denoted in the following as A.
- $C :\ x_i \rightarrow C_i^{(t)}$ is a function that computes the activation degree $C_i \in \Re$ for each concept x_i referring to a discrete time $t = \{1, 2, \ldots, T\}$.
- $f :\ \Re \rightarrow I$ represents the transfer function, which represents the multiple causal impacts on a specific concept for the previously defined activation period.

Depending on how the influence of one factor on the other is to be estimated, the weights w_{ij} are set differently:

- $w_{ij} > 0$, i.e., positive causality,
- $w_{ij} < 0$, i.e., negative causality,
- $w_{ij} = 0$, i.e., no causal relation.

We used pentavalent logic for the weightings' causalities with scalar values:

- -1: strong negative causality,
- -0.5: negative causality,
- 0: no causality,
- 0.5: positive causality,
- 1: strong positive causality.

To calculate the concept values in progress, the following formula is used as activation rule:

Table 1
Classification of hydrothermal reactions (based on [8], updated with current data).

Hydrothermal reaction	Temperature [°C]	Pressure [bar]	Residence time	Main product	References
Hydrothermal carbonization (HTC)					
	190–230	10–30	30 min up to several hours	Bio-coal/char	9, 10, 11
Hydrothermal liquefaction (HTL)					
Low temperature	220–250	40–200	Several minutes	Bio-oil	10, 12
High temperature	>250–400	>40–200	Several minutes	Bio-oil (usually higher yields than for low-temperature)	11, 13
Hydrothermal gasification (HTG)					
Sub-critical	280–374	<221	Seconds up to several minutes	Mainly CH_4	8, 14, 15
Supercritical	>374–800	>221	Seconds up to several minutes	CH_4 at temperatures between 400 and 550 °C and H_2 at temperatures > 550 °C	14, 15
Aqueous phase reforming	200–280	15–50	Several hours	H_2, CO_2 and alkanes from oxygenates	8, 14

$$C_j^{(t+1)} = f\left(\sum_{\substack{i=1\\ i\neq j}}^{n} C_i^{(t)} w_{ij}\right) \tag{1}$$

where n represents the number of concepts, $C_i^{(t)}$ describes the activation degree of concept x_i at the t-th time step, $C_j^{(t+1)}$ correspondingly represents the value of the concept C_j at the time $t+1$ and w_{ij} represents the weighting of the causal connection of the corresponding concepts.

For the preparation of the FCM, we used information on the relationships between the factors from previous work [7,11,17,18]. Based on this, we carried out an expert workshop which was attended by six German scientists working on HTP. In a moderated group discussion, all influencing factors were evaluated regarding their effects on one another and themselves using an impact analysis [20]. An impact matrix developed during the workshop was verified based on the information from the previous work. On that basis, the FCM adjacency matrix A was created.

2.2. Scenario construction and consistency check

The factors' relevance of occurrence, risks in case of non-occurrence and probabilities were used to construct the scenarios for HTP development in Germany. Scenario 1 incorporates the factors with high probability according to Table 2, scenario 2 incorporates the factors with high relevance of occurrence, and scenario 3 considers the probable factors, excluding those with a high risk in the event of non-occurrence. The combinations of factors were selected to reflect the most likely positive development (scenario 1), the most desirable development (scenario 2) and the most likely negative development (scenario 3).

To consider how independent the factors are in their appearance, the scenarios were checked for consistency. Consistency can range from total inconsistency (both projections never occur together) to absolute mutual support (both projections will most likely always coincide) [42]. For this check, a consistency matrix representing the impact values according to the FCM scalar values for the factor combinations was constructed. Table 3 shows the scale relations between the adjacency matrix and the consistency matrix.

To identify whether the scenario combinations are consistent, we calculate average consistency values per scenario. For this, the following steps were performed:

(1) For every scenario, a consistency matrix $\boldsymbol{C}$ representing the degree of consistence was created.

(2) For every matrix, the relevant vectors $c_{ij}^{*} = \begin{pmatrix} c_{ij} \\ \dots \\ c_{nj} \end{pmatrix}; i > j,\ i \in \mathbb{N}$, $i \in \mathbb{N}$ were selected and the average consistency per vector was calculated as $\overline{c_{ij}} = \frac{1}{n}\sum_{i=1}^{n} c_{ij}$

(3) Finally, the overall average per scenario was calculated as $\overline{cons} = \frac{\sum \overline{c_{ij}}}{n_j}$

The procedure described above is in part based on suggestions from Ref. [22]. An average consistency value ($\overline{cons}$) per scenario which is close to 3 indicates that the factor combinations are consistent. If no consistency is reached, the adjacency matrix may be adapted because it serves as the basis for the consistency matrix.

2.3. Scenario-based system analysis

Following the steps in sections 2.1 and 2.2, the scenarios were applied to the FCM to show how the system reacts. To illustrate the system reaction for each scenario, the factors can be set at a value between $+1$ (strong positive concept change) and -1 (strong negative concept change). Within this analysis, a strong impact ($+1$) was distinguished from a less strong impact ($+0.5$). Negative concept change was not applied, as all scenarios assume a positive concept change. The relative change in the system was displayed through a bar graph indicating how the system might react in a given scenario. We used the sigmoid function to generate the variations of concepts, because many complex systems show a progression from small values at the start that accelerate and approach a peak. It is usual for such system assessments to use sigmoid functions if an explicit mathematical model is absent [42]. Additionally, sigmoid FCMs are well suited to qualitative problems that require evidence of the increase, decrease or stability of a concept, especially for strategic decisions based on scenarios [43], which is the case for this study. The system factor dynamics were calculated as follows [44]:

(1) An adjacency matrix A was created representing the concepts' interconnections and intensity of causal interrelations:

$$A = \begin{pmatrix} w_{11} & \cdots & w_{1m} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nm} \end{pmatrix} \tag{4}$$

Fig. 1. Methodological steps to identify and categorize key factors for HTP development in Germany [adapted from 17].

Table 2
Important factors of HTP development in Germany [adapted from 17].

x_i	Tagging	Explanation	Relevance of occurrence	Risk in case of non-occurrence	Probability of occurrence
Political-legal factors					
x_1	Regular fuel recognition	HTP energetic products are recognized as standard fuels. This factor is strongly connected to the fourth factor as this represent an alternative requirement for the recognition of HTP products as standards fuels.	High	High	Uncertain
x_2	Investment and promotion	Investment incentives and/or technology and research funding programs for HTP are being introduced or rather promoted.	Uncertain	Uncertain	Low
x_3	"End of waste" regulation	An end-of-waste regulation is being introduced for HTP products (i.e. products from bio-waste etc.).	High	Uncertain	Uncertain
x_4	Product certification	Official recognition certificates for HTP products are introduced and issued accordingly by the competent authorities. This helps to reduce uncertainty for practice in terms of classification of HTP products as fuels.	Middle	Uncertain	Low
x_5	Thresholds	Thresholds relevant to HTP (e.g. Federal Pollution Control Act) are relaxed as far as reasonably possible.	Uncertain	Uncertain	Uncertain
x_6	Approval procedures	Approval procedures for new HTP plants are accelerated which might save costs during the planning and construction phase.	Uncertain	Uncertain	Uncertain
x_7	Product standardization	The quality of HTP products is standardized. This helps to reduce uncertainties on HTP product and sales markets (e.g. for product user) and enhances transparency.	Middle	High	Low
x_8	Substrate standardization*	The quality of HTP substrates is standardized. This helps to reduce uncertainties on HTP procurement markets (e.g. for substrate user) and enhances transparency.	Low	–	Low
x_9	Process standardization	Process standards are introduced. This helps to reduce uncertainties for plant constructers and operators and enhances transparency.	Low	Uncertain	Uncertain
Economic factors					
x_{10}	Sales markets	The competition on HTP relevant sales and product markets (e.g. energy carriers, fertilizers, substitutes for chemical products) decreases. Thus, the relative market share for HTP firms might be increase.	Low	Middle	Middle
x_{11}	Procurement markets	The competition on HTP relevant procurement markets (e.g. animal excreta, sewage sludge) decreases. Thus, more useable substrates for HTP might be available, also near to the plant location.	Uncertain	Middle	Uncertain
x_{12}	Substrate availability	The available and technically useable amount of substrates increases. Thus, in centralized concepts, plants might handle higher capacities. Or in decentralized concepts, more substrates will be available also near to the plant location assuming that substrate availability increases equally in Germany.	Low	Middle	High
x_{13}	Disposal costs	Disposal costs for HTP substrates per mass unit (e.g. ton) are increasing. Thus, revenues for dispose such substrates might also increases which would generate additional income for HTP plant operators.	Uncertain	Uncertain	High
x_{14}	Material applications*	HTP products are primarily used for material applications (e.g. as fertilizer, functional carbon). This could result if energy markets remain unprofitable due to legal barriers (missing recognition as regular fuels). Products for HTP might be primary applied on markets for bio-based products. However, this factors strongly depends on missing legal adjustments regarding fuel recognition according to expert opinions.	Uncertain	–	Uncertain
x_{15}	Foreign markets**	HTP plant manufacturer and operators concentrate almost exclusively on foreign markets. This might be a result of missing market demand, an insufficient or rather braking legal framework, low relative market shares for HTP products on related markets or missing political incentives and willingness on promoting HTP in Germany.	Uncertain	Uncertain	Uncertain
Technological factors					
x_{16}	Process water treatment	A cost-efficient and sustainable solution for process water treatment is being developed and applied nationwide. This might promote the overall economic (and ecological) performance of HTP as the polluted process water treatment is currently also a relevant cost (economic) factor which might make HTP concepts uneconomic.	Middle	Uncertain	High
x_{17}	System Integration 1*	HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities. Thus, the location of substrate occurrence and treatment facility could be integrated optimally which leads to lower logistic costs. Other synergies might be generated, e.g. process water treatment directly by the wastewater treatment plant on site.	High	–	Middle
x_{18}	System Integration 2*	HTP are increasingly being integrated into bio-refineries. This could also generate considerable synergies (e.g. cascade usage networks).	Uncertain	–	Middle
x_{19}	Nutrient recycling*	The nutrient recovery is enhanced. Especially, nutrient recovery from the process water might be promising as the process water must be treated anyway. Due to political and legal frameworks (2017 amendment of sewage sludge ordinance) that especially require phosphorus recovery from sewage sludge, this might be a useful strategy.	High	–	Uncertain
x_{20}	Learning effects	The process understanding and knowledge increases (learning effects, for example through reference systems/business cases). According to learning curve effect theory this will especially reduce costs per unit of product which is why therefore a techno-economic factor [19].	High	High	High
x_{21}	Accidents**	Accidents with existing facilities reduce trust in the safety of the technology. This might especially effect plant operator and society which is why this factor is strongly connected to social factors.	Uncertain	Uncertain	Uncertain
Ecological factor					
x_{22}	Life cycle performance*	Research on climate and resource protection by HTP will be intensified. Results on this also successively improve the life cycle performance due to new insights. This	Uncertain	Uncertain	Uncertain

(continued on next page)

Table 2 (*continued*)

x_i	Tagging	Explanation	Relevance of occurrence	Risk in case of non-occurrence	Probability of occurrence
		might especially promote social acceptance into the technology. However, the LC performance is strongly connected to several other factors (e.g. reduced pollutants in process water after treatment) which is why this factor is just one part of promoting the LC performance.			
Social factors					
x_{23}	Customer acceptance	Customer acceptance of HTP increases. This might be the result due to technological progress, legal adjustments that promote HTP, higher transparency regarding HTP products quality (e.g. end-product customers), substrate quality and process performance (e.g. customer for facilities/plant operator).	Uncertain	Uncertain	Uncertain
x_{24}	Social acceptance	Social acceptance on HTP increase or rather society takes HTP as resource efficient technology for future biomass conversion stronger into account.	Uncertain	Uncertain	Uncertain

Explanation of asterisks:
* According to expert estimations, this factor is not considered as a risk if it not occurs. The corresponding field in the table is therefore filled with "-".
** According to expert estimations, this factor solely represents a risk. Hence, occurrence will have a negative effect.

Additional notes:

1) For the relevance, risks and probabilities of the factors that are described as “uncertain”, no expert consensus was reached in the mentioned Delphi survey [cf. 17], which is why these factors estimations were classified as uncertain.
2) In the referenced study [17], the factors relevance and probabilities are classified by a ranking. In the present work, we use an easier understandable verbal classification based on this ranking, i.e. High (Rank 1–3), Middle (Rank 4–6), Low (Rank > 6).
3) The underlying ranking was created for each individual category using the fuzzy Delphi method, which is based on an expert Delphi survey among 51 European HTP experts. There were two rounds of surveys (1st round: 27 responses; 2nd round: 12 responses). For all categories (i.e. “Relevance of occurrence”, “Risk in case of non-occurrence”, “Probability of occurrence”) the factors in the original questionnaire were assessed using a Likert scale from 1 (e.g. less relevant) to 5 (e.g. high relevant) assessed by the experts. The results were transferred to a fuzzy scale [cf. 20], evaluated by FDM and transferred to a ranking according to the result (see footnote 2). According to the questionnaire sent, the categories mentioned here are defined as follows:

- Relevance of occurrence: Events or factors that are considered to be particularly important, if the future development of HTP in Germany is to be pushed (e.g. construction of industrial plants).
- Risk in case of non-occurrence: Events or factors whose non-occurrence is considered to be particularly problematic, if the future development of HTP in Germany is to be pushed.
- Probability of occurrence: Events or factors that are estimated as particularly likely to occur by 2030.

Table 3
Scale adaption of FCM scale into consistency matrix scale.

Consistency matrix linguistic meaning	Consistency scale	FCM scale
Total inconsistency: both projections never occur together.	1	not detectable
Partial inconsistency; i.e., the two projections influence each other. Their common occurrence affects the credibility of the scenario.	2	−0.5; −1
Neutral or independent of each other; i.e., the two projections do not affect each other and their appearance does not affect the credibility of the scenario.	3	0
Mutual benefit; i.e., the two projections may well occur in a scenario.	4	0.5
Very strong mutual support; i.e., due to the occurrence of the one projection, the occurrence of the other projection can be expected.	5	1

(2) The initial vector state was denoted as follows:

$$\overrightarrow{X}^{0} = (x_1{}^{o}\ x_2{}^{o}\ \dots\ x_n{}^{o}) \tag{5}$$

(3) The scenario-based values of the concepts (initial state changes) were calculated with an activation function ($f(x)$), in this case the sigmoid function. For this, the initial concept states were varied according to the corresponding scenario:

$$\overrightarrow{X}^{t+1} = f\left(\overrightarrow{X}^{t+1} * A\right) = \left(x_1{}^{t+1}\ \ x_2{}^{t+1}\ \ \dots\ \ x_n{}^{t+1}\right) \tag{6}$$

(4) The state changed throughout the processes. The inference process stopped when stability was reached. The final vector state showed the effect of concept changes on the whole system of concepts.

3. Results

3.1. FCM for HTP system factors

Based on the process presented in Fig. 1, we created the following adjacency matrix A that represents the interconnections of the concepts. The matrix is based on assessments from the expert workshop in which six HTP experts from the German Biomass Research Centre and the corresponding author participated (cf. Fig. 1). In the workshop, the participants assessed the causalities between the individual factors qualitatively. Based on this, an impact matrix was created, which was finally transferred to the adjacency matrix shown in Table 4. Further details are described in Ref. [17].

The FCM also represents these interconnections, but in a visualized form. The map was created with the online software Mental Modeler [45]. For transparency reasons, we appended a description of how the model can be rebuilt based on the adjacency matrix using Mental Modeler (see Appendix).

To give an impression of the complexity of the FCM, Fig. 2 shows a part of the map for political-legal concepts. We decided to show this part of the FCM because the political-legal concepts have the highest impact of all the concepts on the overall system [45–47].

The numerical values represent the weight w_{ij} of the directed edge of each concept pair. It can be seen that “Regular fuel recognition” in particular has a strong influence on other concepts, indicated by the various relations marked “+1”. In general, the occurrence of this concept positively influences other system concepts. The weight “0”, which represents no causal relation between the concepts, is not visualized.

3.2. HTP development scenarios by 2030

Based on the methodology described in section 2.2, the scenarios presented in Table 5 were created.

The respective factor combinations indicate which of the factors listed in Table 2 occur in the respective scenario. The first scenario includes mostly technological changes, and so it is referred to as the

Table 4
Adjacency matrix: FCM factors and concepts relationships according to expert knowledge and relevant literature [own presentation].

x_{ji}	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}
x_1	0	1	1	−1	1	1	1	0	0	−0.5	0	−0.5	−0.5	−0.5	−0.5	1	0	0	0	0	−0.5	0	0.5	1
x_2	0	0	0	0	0	0	0	0	0	−0.5	0	0	0	0	0	0	0.5	0.5	0	0.5	0	0	0	0
x_3	1	0	0	−1	1	0.5	0.5	0.5	0.5	−0.5	−0.5	−0.5	−0.5	−0.5	−0.5	1	0	0	0	0	0	0.5	0.5	1
x_4	−1	0	−1	0	1	1	1	0	0	0	−0.5	0	−0.5	−0.5	−0.5	0.5	0	0	0	0	0	0	0	1
x_5	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x_6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−0.5	0	0.5	0.5	0	0	0	0	0.5	0
x_7	0	0	0	0	0	0	0	0	0	−0.5	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
x_8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5	0	0	0	0	0	0.5	0.5	0.5
x_9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	−0.5	0	0.5	0.5
x_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−0.5	0	0	0	0.5	0	0	0	0.5	0
x_{11}	0	0	0	0	0	0	0	0	0	0	0	0	−0.5	0	0	0	0	0	0	0	0	0	0	0
x_{12}	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0
x_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
x_{14}	0	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0.5
x_{15}	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
x_{16}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5
x_{17}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0.5	1	0	0	0.5	0.5	0.5
x_{18}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0.5	0	1	0	0	0.5	0.5	0.5
x_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	1	0.5	0.5
x_{20}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	−0.5	0	0	0	0	0	0	0.5	1	0.5
x_{21}	0	0	0	0	0	−0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	−0.5	0	0	−1	−1
x_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5
x_{23}	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
x_{24}	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

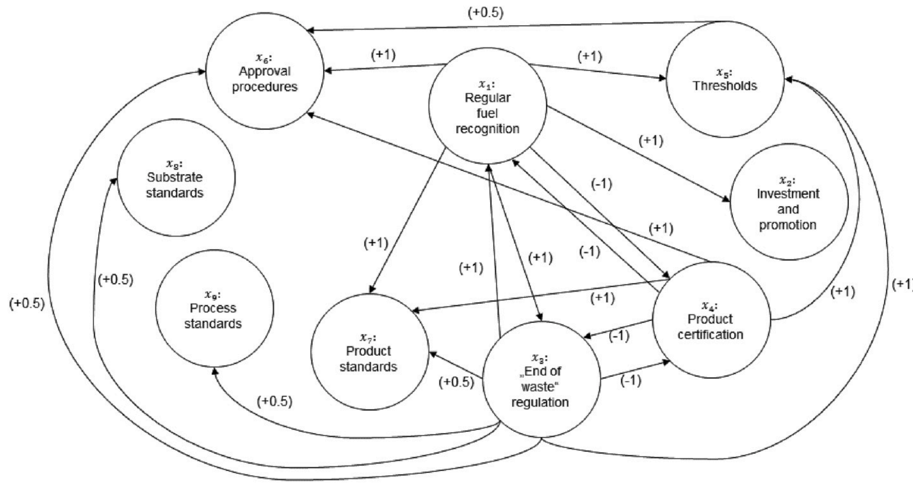

Fig. 2. FCM based on expert knowledge for political-legal concepts (own presentation).

Table 5
HTP scenarios for Germany by 2030.

HTP Scenario	Scenario factor combination and description
Technological Action $\overline{cons} \approx 3$ Consistent	*Factor combination* $= \{x_{12};\ x_{13};\ x_{16};\ x_{20}\}$ The available and useable amount of substrates increases (x_{12}). Disposal costs for HTP substrates (e.g., sewage sludge) are increasing (x_{13}). A cost-efficient and sustainable solution for process-water treatment is being applied (x_{16}) and in general, learning effects can be observed (x_{20}).
Legal and Technological Action $\overline{cons} \approx 3.3$ Nearly consistent	*Factor combination* $= \{x_1;\ x_3;\ x_{17};\ x_{19};\ x_{20}\}$ HTP energetic products are recognized as standard fuels, largely based on an end-of-waste regulation for HTP products (x_1; x_3). HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities (x_{17}). The nutrient recovery is enhanced (x_{19}), and, in general, learning effects can be observed (x_{20}).
No Action $\overline{cons} \approx 3.2$ Nearly consistent	*Factor combination* $= \{x_{12};\ x_{13}\}$ The available and useable amount of substrates increases (x_{12}). Disposal costs for HTP substrates (e.g., sewage sludge) are increasing (x_{13}). Although the risk in non-occurrence of an efficient process water-treatment is rated as uncertain, we excluded this factor here, because, based on discussions with experts, we see this as a serious risk. Learning effects are excluded, as their non-occurrence is seen as a serious risk.

"technological action" (TA) scenario. The second scenario includes also legal changes and is thus named the "legal and technological action" (LTA) scenario. The substrate and disposal cost increases are factors that are not directly influenced by specific actions, which is why the last scenario is named the "no action" (NA) scenario.

As mentioned in section 2, when considering the system reactions, we distinguish between strong (+1) and weak (+0.5) impacts of the factors. It should be noted that for factors that either occur or fail to occur, no distinction can be made between strong and weak impacts. In this study, this point concerns only the legal framework conditions, as these are either introduced or not; we cannot make a substantiated distinction between weak and strong impacts in the legal framework conditions.

The following matrices were used to calculate the average consistency value for each scenario (cf. $\overline{cons}$ in Table 5) according to formulas (2) and (3).

$$C_{probable} = \begin{array}{c} \\ x_{12} \\ x_{13} \\ x_{16} \\ x_{20} \end{array} \begin{pmatrix} x_{12} & x_{13} & x_{16} & x_{20} \\ 3 & 4 & 3 & 3 \\ 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 \end{pmatrix}$$

$$C_{relevance} = \begin{array}{c} \\ x_1 \\ x_3 \\ x_{17} \\ x_{19} \\ x_{20} \end{array} \begin{pmatrix} x_1 & x_3 & x_{17} & x_{19} & x_{20} \\ 3 & 5 & 3 & 3 & 3 \\ 5 & 3 & 3 & 3 & 3 \\ 3 & 3 & 4 & 5 & 3 \\ 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \end{pmatrix}$$

$$C_{risk} = \begin{array}{c} \\ x_{12} \\ x_{13} \end{array} \begin{pmatrix} x_{12} & x_{13} \\ 3 & 4 \\ 3 & 3 \end{pmatrix}$$

3.3. FCM system reaction to scenarios

We want to emphasize once again that the analysis is semi-quantitative and the results are primarily based on expert knowledge and not on quantitative data. The quantification step uses the mathematical procedure of the FCM explained in section 2. It should be noted that the variations represent corresponding changes until 2030, and some factors do not refer to the actual state. This is because certain factors are currently not observable. Fig. 3 shows the system reaction per scenario.

4. Discussion

4.1. Interpretation of system reaction to scenarios

The TA (hI) scenario has a relatively small impact on the system and affects just five factors. Thus, the system generally reacts robustly to this scenario, which suggests a stable development that, apart from the scenario factors and the factors influenced, corresponds to the status quo. The economic factors show the strongest reactions. The competition in the procurement markets is decreasing, which can be explained by the increasing amount of substrates. Due to the assumed largely positive technological development and the decreasing production costs per unit reasoned in the assumed learning effects, the willingness of the actors to concentrate on foreign markets is decreasing. However, this effect is quite small, as there is still a rather restrictive legal framework in Germany, that still hinders the energetic use of HTP products as standard fuels.

In the NA (hI) scenario, there are very few changes to the status quo,

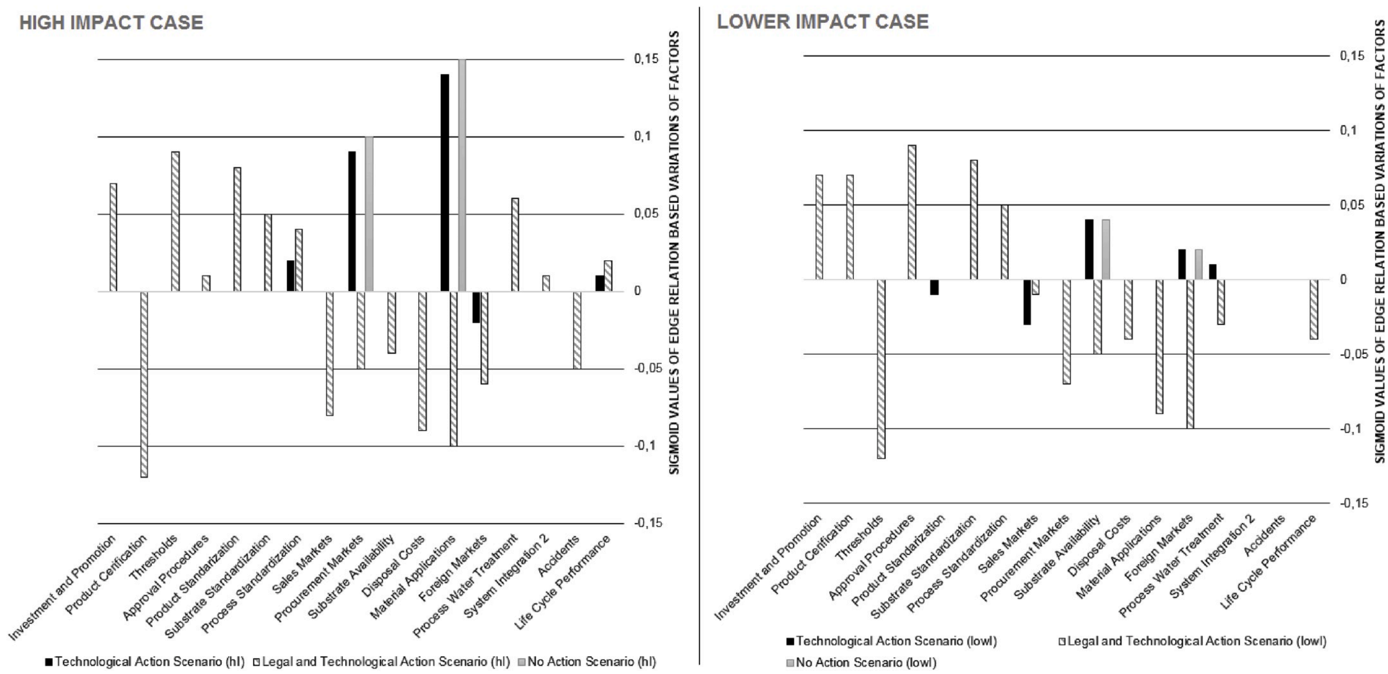

Fig. 3. FCM system factors variations for each HTP scenario assuming high factor (hI) and lower factor (lowI) impact.
* For factors that are not listed (e.g., x1; x3; x19; x20), the change is "0" for all variants and scenarios, which is why they are not included in the figures.

which is due to the fact that only two scenario factors occur. The competition in the procurement markets tends to decline, which is due to the increasing amount of substrate. The development of HTP according to this scenario is stagnant.

The greatest number of effects can be observed in the LTA scenario. This is mainly due to the high impact of the assumed legal adjustments. As can be seen in Fig. 2, "regular fuel recognition" has a high impact on the overall system and influences several factors directly. Approval of HTP products as energetic products provides legal certainty regarding energy use, which could have various effects. For example, the likelihood of investment and technology funding could increase, and the market for material applications could become less attractive as the energy market is now fully accessible for HTP products. Furthermore, the approval of HTP products as a standard fuel makes product certification largely obsolete, which is reflected in the negative value of this factor. The competitive situation in the procurement and sales markets is therefore exacerbated by the likely increase in the number of actors in the HTP branch. Foreign markets also lose their appeal as a result of the supporting legal framework. As HTP development gathers momentum, standardization processes could become more frequent. Planning and approval procedures could be also simplified. Technological development could also increase, probably due to development dynamics, as evidenced by the high likelihood of introducing a cost-effective process-water treatment.

In the LTA (lowI) scenario, the difference to the high-impact case is very small, because it is still assumed that the legal changes are introduced. This clearly shows the high relevance of the legal factors.

In the NA (lowI) scenario, the same system factors react as in the high-impact case, albeit with a much lower severity. The strength of the scenario factors therefore disproportionately affects the system factors in this scenario.

Most of the differences between high and low-impact cases appear in the TA scenario. In the lower-impact case, for example, the probability of occurrence of process standards is reduced, which may be due to the less pronounced learning effects and technological advances in process-water treatment. As technological advances are less pronounced, it may be more difficult to achieve uniform process standards based on generally accepted best available techniques. This difficulty is also reflected in the fact that the factor "approval procedures" shows a negative value, and so it is less likely that approval procedures will be simplified in this scenario. Interestingly, the factor "foreign markets" has a positive value. The lower factor impact in this scenario is not enough to reduce the interest of the branch in foreign markets.

4.2. Comparison of results for Germany with those of other countries

To the authors' knowledge, there are no comparable studies for other countries. Nevertheless, some literature is available on current development potential and obstacles outside Germany. For example, [48] mentioned the potential for HTC in Europe as an innovative technology for the production of growing-media alternatives (e.g., peat). However, the study does not make a detailed assessment of other potentials and obstacles. [49] discussed future perspectives of hydrothermal conversion for the production of fuels and energy carriers, but without a geographical focus. In their opinion, the technology has reached industrial maturity; however, research into suitable and stable catalysts and handling of the liquid phase from HTC and HTL, for example, is still necessary for economic feasibility. [50] analysed the suitability of HTC for food waste treatment in China and recommended to use it for this purpose combined with anaerobic digestion.

The results of the studies mentioned are consistent in individual points with the present study. However, the mentioned studies do not consider an overall system of factors. For international readers, this study can provide first hints about potentials and obstacles, because many factors apply not only to Germany. The legal problem of fuel approval applies to the whole of Europe. In addition, the central techno-economic problems and potentials apply beyond Germany (e.g., treating the process water).

4.3. Limitations of this work and suggestions for further research

This study is mainly based on expert knowledge and thus on qualitative information. This is because there is little reliable historical data for the development of the relevant system factors. Deterministic models, which mathematically describe the relationship of the factors to one another, do not exist. Previous studies have shown that the FCM is a method well-suited for such analyses as it does not require quantitative inputs and can provide helpful results based on qualitative descriptions and relationships. Although the results are largely based on qualitative expert assessments, through the broad participation process and the evaluation and analysis of information using fuzzy logic, they can be seen as reliable.

The main contribution of this study is the systematic creation and comparison of different development paths for HTP until 2030. This contribution can help decision-makers in business, science, politics and civil society to identify bottlenecks for HTP in Germany. Future studies could expand the system by including new factors that could be identified by further expert knowledge. The relationships between the factors can be updated based on potential new information. In addition, other scenarios (i.e., factor combinations) could also be considered with regard to their effect on the system to identify further correlations. Future studies should at least partially elaborate deterministic models and validate them with available data, as far as possible and reasonable.

5. Conclusion and recommendations

The purpose of this study was to comprehensively map the system of factors in scenarios of HTP in Germany and analyse their reactions. This is unique because it attempts to describe the complete system of factors for the future development of HTP in Germany and their interactions. The study supports previous analysis of the authors with further findings.

The legal factors have a large influence on the system. Based on this analysis, approval of HTP products as regular fuels is a prerequisite for creating legal certainty for the energetic use of the products. The model shows that this legal certainty in turn has various effects; for example, product certifications are less necessary, foreign markets lose relevance for domestic companies, technology funding and the establishment of substrate and process standards is more likely. A recommendation of this study is therefore that HTP products should be legally recognized as products, because the positive effects for the development of the technology are significant. Specifically, in EU or national waste law the legislator could specify the so named "End of waste" status of HTP products according to Article 6 Waste Framework Directive.

Techno-economic factors (e.g., efficient process-water treatment, nutrient recycling, learning effects) also have an impact on the overall system, but less than the legal factors, which is shown by the different reactions in the TA and LTA scenarios. Nevertheless, these factors are also important for the development of HTP and they are to be implemented in conjunction with the legal factors. Hence, also technology funding is recommended, including the development of a cost-efficient process-water treatment, integrated approaches such as nutrient recycling, and the supporting of the construction of the facilities in industrial continuous operation in Germany.

The methodological framework and analysis presented in this paper can support policy-makers regarding legislation and technology funding. The results are also useful for science because they allow for an improved prioritization of research.

The value added by this study lies in the fact that development paths for HTP were derived, the system effects were analysed through FCM analysis and thus the understanding of the system was increased. The influencing factors were previously known and prioritized, but their effects on one another had not been analysed. It is critical to note that the analysis does not offer objective accuracy and is based not on quantitative data but on qualitative expert statements. Nevertheless, the study presents trends and their effects, which can support future decisions.

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Appendix

Short manual for rebuilding the fuzzy-logic cognitive map and calculate the system reactions:

1. Visit the website www.mentalmodeler.com.
2. Create a login as described on the website.
3. After you have access to the tool, activate your Flash Player.
4. In the "Model" tab, enter all the factors listed in Table 1 (as boxes). The program automatically assigns "fuzzy set" values.
5. Then switch to the tab "Matrix" and enter the values for the connections between the factors acc. Table 4.
6. Then go to the tab "Scenario" and create the scenarios acc. Table 5. Select "sigmoid" as the calculation form.
7. Now vary between high impact (+1) and lower impact (+0.5) cases.
8. Mental Modeler will now give you the scenario values that should match with Fig. 3.

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Paper VI

The following text reassembles the full text-version of the article.

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RESEARCH AND ANALYSIS

Hydrothermal carbonization for sludge disposal in Germany

A comparative assessment for industrial-scale scenarios in 2030

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Abstract

The efficient use of biogenic residues can make a significant contribution to increase resource efficiency. Due to its high energy efficiency, hydrothermal carbonization (HTC) is being discussed as a potentially suitable technology for particularly wet and sludgy biogenic residues. In Germany, however, it has not yet been established at industrial continuous operation. Among others, this is due to missing solutions for the economic treatment of the high organic loads in the liquid by-product and insufficient knowledge on long-term processing. Nevertheless, it is still expected that HTC could be able to contribute in the future, especially for sewage sludge disposal. Whether and under what conditions this could be the case is the subject of this study. The competitiveness of modeled cases for industrial sewage sludge HTC, which address different future paths, compared to thermal sludge treatment is investigated by using a multi-criteria instrument. Results show that HTC can only compete with the reference technology if certain framework conditions are given. Particularly, an efficient phosphorus recycling should be integrated and the production costs of the solid product should be at least less than €325 per metric ton according to this case study. The treatment performance of the liquid phase should be as high as possible whereby costs for further treatment equipment should be minimized, so that mentioned productions costs are not exceeded. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
hydrothermal carbonization, industrial ecology, multi-criteria decision-making, sludge disposal, technology assessment

1 | INTRODUCTION

With the latest sustainability strategy, the German Federal Government has set various goals for climate and resource protection (Bundesregierung, 2016). For example, annual greenhouse gas emissions are to be reduced by 55% in 2030 compared with 1990 levels and primary energy consumption by 50% in 2050 compared with 2008 levels. To reach these goals, among others, the recycling of limited raw materials is aimed to reduce the use of primary raw materials (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). The sustainable production of biomass and their conversion into food, feed, bio-based products, and bioenergy is another central aim, which is often summarized as "bio-economy" (European Commission, 2012). To increase resource efficiency, the gradual recycling and multiple use of natural resources is being pursued (BMEL, 2014). All this requires also the more efficient use of biogenic residues.

Considering the explained background, hydrothermal carbonization (HTC) is currently being discussed as a potentially suitable conversion technology for the treatment of biogenic residues with high water content (Heidari, Dutta, Acharya, & Mahmud, 2018; Reißmann, Thrän, & Bezama, 2018; Wang, Zhai, Zhu, Li, & Zeng, 2018). HTC is a thermochemical process that produces a solid carbon product. Liquid and gaseous by-products are also produced (Medick, Teichmann, & Kemfert, 2017). In current practice (pilot plants), the reaction usually takes place continuously or in a batch process at 200–210°C, 20–25 bar, and within 3–6 hr of residence time (Anderer, 2012; Blümel et al., 2015; Kusche & Ender, 2018). One of the convincing features of HTC is its high energy efficiency. Since water is used as reaction medium anyway, energy- and cost-intensive drying of the substrate prior to the process is not necessary (Escala, Zumbühl, Koller, Junge, & Krebs, 2013). However, there are currently some obstacles that hinder the industrial application of HTC in Germany. In particular, the disposal of the liquid by-product (so-called process water) requires a cost-efficient treatment, which has not yet been conclusively developed (Fettig et al., 2018). Additionally, experiences in industrial continuous operation are missing in Germany so far (Reißmann et al., 2018). Nonetheless, it is expected that HTC may offer a potential alternative in the treatment of sewage sludge (Reißmann, Thrän, & Bezama, 2018a). Particularly, due to adjustments to the fertilizer law (BMUB, 2017) and the sewage sludge ordinance (BMJV, 2017), alternative sludge utilization options with integrated phosphorus recovery will gain in importance in the future.

Whether hydrothermal processes (HTP) can contribute to the future resource efficient treatment of biogenic residues in Germany is currently difficult to assess. Therefore, with previous studies, potentials and obstacles for the development of HTP in Germany were identified by means of a literature review, expert interviews, and a SWOT analysis (Reißmann et al., 2018; Reißmann et al., 2018a). Based on these studies and further representative expert assessments, which were collected through a Delphi survey, three future paths for the development of HTP in Germany until 2030 were constructed. The expert panel of the Delphi survey consisted on various stakeholder groups: science and research (65.5%), business (27.3%), associations and NGOs (3.6%), politics and administration (1.8%), and multipliers (1.8%). The focus was on actors from the scientific field, since HTP is mainly known in the research community and most of the experts are part of this community. A high proportion of around 70% of the scientists surveyed have an environmental background. The survey asked questions about the weighting of the criteria and asked the experts to use the analytical hierarchy process (AHP) scale according to Saaty (Saaty, 1990). In addition, questions were asked about various aspects of the future development of HTP in Germany until 2030. Experts should assess events for their relevance, likelihood, and risk of non-entry for successful technology development. The assessment was based on a Likert scale from 1 (not very relevant/likely …) to 5 (very relevant/likely …). The proposed criteria and events were identified by previous formats (workshops, interviews, literature reviews) (Reißmann et al., 2018a; Reißmann, Thrän, & Bezama, 2018b). Using the Fuzzy Delphi Method (FDM) and fuzzy cognitive mapping (FCM), development factors with particularly high relevance and probability of occurrence by 2030 were determined and their connections presented (Reißmann et al., 2018b). As a result, the following scenarios were derived. The scenarios are not intended to predict a certain future but to show a "development funnel", which can help to reduce uncertainty of future decisions within this context.

- *Technological Action Scenario (HTC-TA):* This scenario represents the most likely development by 2030 according to expert assessments and evaluation using FDM and FCM. Accordingly, the available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g., sewage sludge) will increase by 2030. Depending on the individual case, high-performance treatment concepts are used for the process water. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed. This means that if the cumulative output quantity (here: solid product of HTC) is doubled, the production costs are reduced by a factor (so-called learning rate) of a maximum of 30% (Coenenberg, 1999).
- *Legal and Technological Action Scenario (HTC-LTA):* This scenario represents the most relevant development of supporting factors according to expert assessments and evaluation using FDM and FCM. HTP plants are used decentral and integrated into suitable waste and waste water treatment plants. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed (for explanation, see HTC-TA scenario). Products made of HTP with waste and residual materials as substrates are legally permitted as standard fuels. Nutrient recycling (e.g., phosphorus) is basically integrated into HTP.
- *No Action Scenario (HTC-NA):* This scenario represents the probable development path, excluding factors whose non-occurrence poses a particular risk according to expert assessments and evaluations using FDM and FCM. Accordingly, the available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g., sewage sludge) will increase by 2030.

At this point, it should be pointed out that ecological and social factors should also be included for a comprehensive HTC scenario analysis: the long list in Reißmann, Thrän, and Bezama (2020), which calls "life cycle performance" as an ecological factor and "customer acceptance" and "social acceptance" as social factors, has clearly indicated in this regard, as well. However, due to insufficient data, these factors could not be considered in the present analysis.

To clarify to what extent the individual scenarios differ along the HTC process chain and where the system boundary is set, Figure 1 gives an overview of the relevant factors along the different scenarios and their connection to corresponding process steps.

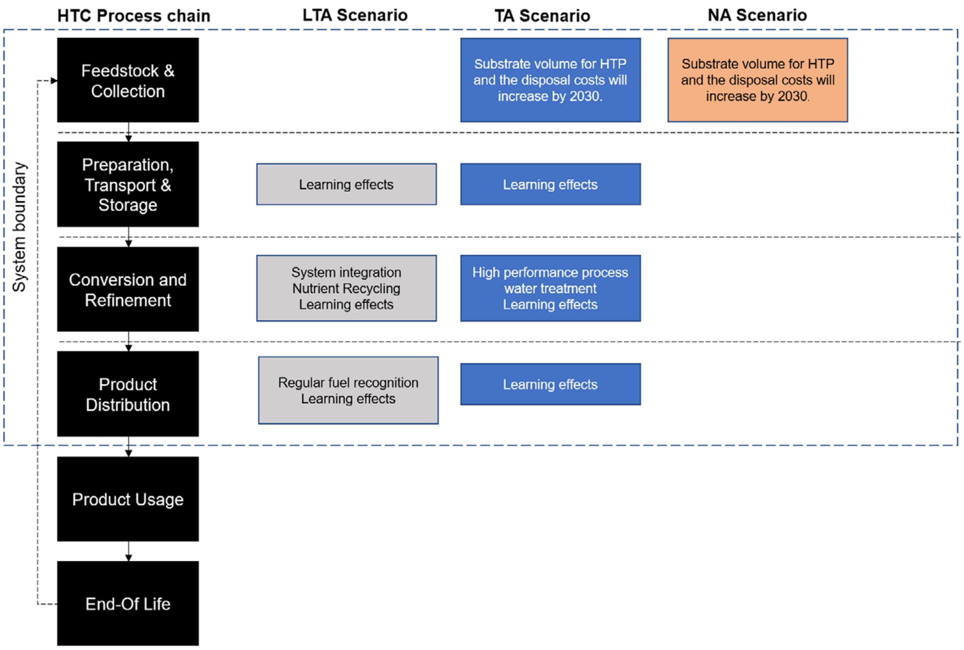

FIGURE 1 System boundary of scenario analysis and corresponding scenario factors along the HTC process chain
Note. HTP = hydrothermal processes; HTC = hydrothermal carbonization; TA = technological action; LTA = legal and technological action; NA = no action.

Parallel to the aforementioned preliminary work, a technology assessment tool for HTP was developed (Reißmann, Thrän, & Bezama, 2018c), which can be used to assess the future paths and compare them to a reference technology. The evaluation tool was specially developed for HTP, which is reflected in the tailored criteria that were derived in a transparent procedure involving various stakeholders (cf. Reißmann et al., 2018a).

This analysis follows on from this previous work. On the one hand, the assessment instrument will be used for the first time to comparatively analyze HTP industrial scale scenarios and, on the other hand, potentially promising development corridors shall be derived for this exemplary case study (which, however, cannot be generalized). The novel contribution of this study is that for the first time (modeled) industrial HTC applications for potential development paths in Germany are quantitatively and comparatively evaluated. Although the literature shows that other studies also consider HTC using multi-criteria assessment tools, no future developments are considered and no geographical focus is set on Germany. For example, Qazi, Abushammala, and Azam (2018) evaluate various waste-to-energy processes, including HTC, using several criteria. Suwelack (2016) also presents an MCA instrument, which is applicable for the evaluation of HTC and describes first steps for implementation. However, a comparative analysis of different industrial HTC applications including possible future developments is not carried out.

The aim is to illustrate how the technology assessment instrument and the scenarios can be used to derive initial benchmarks for the future techno-economic development of HTC at the plant level in Germany. In general, orientation values can also be derived for other areas (e.g., environmental protection), but this study focuses on the techno-economic area. The evaluation is based on data for the semi-technical scale and is also intended to validate the application of the assessment instrument. Further work should substantiate the results, for example, on the basis of further cases, scenarios and by considering further parameters and sensitivities.

2 | METHODS

2.1 | Base case and reference technology

As starting point, a HTC base case for sewage sludge disposal in Germany is created, which reflects a possible technological state in 2030 based on current best available techniques (BAT), but does not yet include any learning effects. Due to the topicality and availability of data, we designed the base case on investigations by Blöhse (2017) on the use of HTC as sludge disposal technology in Germany. These data are based on laboratory tests supported by experiences in the semi-technical scale, which were converted to the large-scale (for detailed information on the data curation and calculation cf. Blöhse, 2017). Since there is a lack of experience in industrial continuous operation and corresponding data sets so far, this analysis represents the most suitable and available data source for the study subject. Accordingly, the technological framework conditions of the base case are shown in Table 1. A visualization of the base case can be found in File S1.

TABLE 1 Base case for sewage sludge HTC representing current BAT

Category	Settings
Substrate input	• Municipal sewage sludge (mechanically dewatered) • 65,000 tons of fresh mass per year • 14,300 tons of dry matter per year (~dry residue content of 22% of the fresh matter) corresponds approximately to a sewage treatment plant with one million population equivalents
Conversion technology	• Continuous operated HTC on an industrial scale • Plant capacity corresponds to substrate input • Processing conditions: 220°C, 2 hr, 15 bar, pH value 7–8, no process optimization
Site and logistics	• HTC plant in a distance of 20 km from the wastewater treatment plant (simplified assumption for central treatment and to exclude assumption “system integration” in the base case) • HTC plant 40 km away from incineration plant
Mass reduction	• 75% of fresh matter input
Product yield	• 68% of dry matter input
COD load	• 278 kg/t dry matter input
Process water treatment	• Anaerobic COD elimination (fermentation), elimination of 70% of COD load
Other by-products for treatment (not considered due to insufficient data)	• Sludge water from first dewatering stage • Exhaust air and condensate (vapors) • HTC process gas
Nutrient recycling	• Excluded in base case
Product use	• Mono incineration in sewage sludge incineration plant as a material to be disposed of

A reference technology representing the current state of the art for sewage sludge treatment serves as a benchmark for the base case and the correspondingly adapted scenario cases. The reference technology for reducing the mass of the sewage sludge is thermal drying up to a dry matter content of 90%, followed by mono-combustion and storage of the phosphorus containing ashes (cf. Blöhse, 2017).

2.2 | Data and assessment criteria

The next step consisted in collecting the necessary information for the technology assessment of the base case. According to Reißmann et al. (2018a), the criteria shown in Table 2 shall be considered when evaluating HTC.

Some of the listed criteria are excluded from the further analysis (marked in bold in Table 2). The TRL is neglected as it is assumed that all cases have reached industrial maturity (i.e., TRL = 9) and thus there are no differences. Due to insufficient and incomparable data, the GHG emissions are also excluded. Comparable GHG balances are necessary for all case studies that are currently not available. GHG calculations already exist for sewage sludge HTC (e.g., Meisel et al., 2019), but not for the case constellation considered here. In order to avoid misinterpretations, this criterion is therefore not considered. The criteria “calorific value of end-product” and “carbon share of end-product” are excluded because they refer to product qualities for potential sales markets or certain fields of application (energy market, carbon sequestration) which are not relevant in the case of sewage sludge disposal.

The decisive factor is that the values of the remaining criteria (i.e., all criteria that have not been marked in bold in Table 2) are calculated or collected on the basis of comparable assumptions. This is reflected in this study, as all the case studies are based on the same basic assumptions (cf. Table 1 for base case assumptions and Table 3 for scenario assumptions) and the same database (i.e., Blöhse, 2017). It should be noted that the criteria are not entirely independent and partly influence each other. However, the holistic presentation of relevant criteria mostly requires this, which is why various studies point out that complete independence of the criteria in practical application is often hardly achievable. Nevertheless, redundancies should be minimized in any case, which is also considered in this assessment (cf. Billig, 2016; Wilkens, 2012).

Regarding investment and operating costs per HTC plant, the following differentiation was assumed. An average of €12 million was considered as the investment cost for HTC plants with simple plant technology, whereas €20 million were considered for HTC plants with complex plant technology. Moreover, 2.5% of the investment was considered as an average of the operating resources and six employees with an average annual salary of €50,000 for a period of 30 years were assumed. The phosphorus recovery is initially excluded within these values and the investment and

TABLE 2 Criteria for technology assessment of HTC (Reißmann et al. 2018a)

Criteria	Description	Unit(s)
Technology readiness level (TRL)	Classification of the level of development of a considered technology according to ISO 16290.	Ordinal scale (1–9)
Production costs per unit	Raw material costs, manufacturing costs, investment and operating costs for one mass unit of the product whereby no further refinement steps are included (e.g., pelletizing). In the following calculation, we differentiate between variable and fixed costs. Investment costs are part of the fixed costs and are calculated in EUR/ton of solid product. Also, energy and amortization are integrated into these calculations, for example, we integrated cost savings for the substitution of methane for electrical and thermal energy into the calculation. Regarding the amortization of investment cost, we referred to Blöhse (2017) as follows: investment: 70% operation technique (cap. = 15 a), 20% building equipment (cap. = 30 a), 10% E-MSR technique (cap. = 10 a), max. time = 30 a. The detailed calculations are part of Reißmann et al. (2020a).	Euro per ton solid product
Conversion efficiency/mass balance	Relation of product output to raw material input (mass related).	Percent of mass unit
Energy efficiency/energy balance	Energetic effort for the production, operation, and reuse (disposal or recycling) of the product (energy balance) in relation to the energetic output of the product (efficiency).	Percent of energy unit
Distance of plant to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Distance in kilometer
Greenhouse-gas (GHG) emissions	Greenhouse-gas emissions occurring through the process steps relating to the system boundaries. For this analysis, system boundaries include transport and conversion steps. All other steps (e.g., product usage) are excluded as there are no difference between the cases.	Global warming potential (CO_2 equivalent)
Pollution of process water	Share of organic substances in process water that occurs after hydrothermal processing.	Chemical oxygen demand in mgO_2/l
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in phosphorus content.	Percent of mass unit
Calorific value of end-product	Maximum usable heat amount through the combustion of the end-product (water free).	Energy unit per mass unit
Carbon share of end-product	Share of carbon in HTC coal in relation to total mass volume of the product.	Percent of mass unit

Note: Criteria in bold are excluded from the further analysis.

resource requirements for the process water treatment are included on an assumption basis. The more complex plant technology is considered for the scenarios with more efficient process water treatment and integrated nutrient recycling (i.e., TA, LTA). For thermal drying, the investment sum is estimated at €5,000,000 over 30 years. Operating costs, staff costs as well as costs for the treatment of vapors and condensate are not included for thermal treatment in order to keep the estimation conservative. The detailed calculations for the individual criteria, broken down according to the various case studies, are available as supporting data in Reißmann, Thrän, Bezama, and Blöhse (2020a) and Supporting Information Files S2 and S3.

2.3 | Scenario factor effects on assessment criteria

The initial criteria values of the base case are then varied according to the scenario assumptions. Table 3 shows the assumptions used to represent the factor and the resulting effects on the individual evaluation criteria. The description of the factors is part of Reißmann et al. (2020a).

2.4 | Technology assessment of HTC cases and reference technology case

Subsequently, all cases are evaluated with the technology assessment tool and compared to the reference technology. The technology assessment will be based on Reißmann et al. (2018c). For details on the methodology, reference is made to this study. According to this, the criteria are first weighted by the analytical hierarchy process (AHP) (Saaty, 1990) and then evaluated comparatively using the technique for order preference by similarity to ideal solution (TOPSIS) (Hwang & Yoon, 1981). Expert assessments were used to weight the criteria according to the AHP. For this

TABLE 3 Scenario factors, assumptions for the presentation of the factor and factor effects on the evaluation criteria

Scenario factors/descriptors	Assumption for representing the factors	Factor effects on assessment criteria
Regular fuel recognition for HTC solid product	The legal framework allows for regular energy sales of the HTC solid product. However, as it is hardly foreseeable from a current perspective whether customers are actually willing to pay a price for the solid product from HTC, this scenario factor is pragmatically included by eliminating the disposal costs at the sewage sludge incineration plant. The reason is that it is assumed that because of the legally guaranteed fuel quality of the solid product, operators of, for example, (heating) power stations to waive the collection of disposal costs for this substitute fuel. From the perspective of the authors, this assumption is most likely as a possible practice.	*Production costs per unit*: Since the product from HTC is now legally considered a fuel, the operators of the sewage sludge incineration plant do not charge disposal costs (here: €80 per ton).
Substrate availability and disposal costs	An increase in the substrate supply is believed to increase the disposal cost of sewage sludge, that is, there will be higher disposal costs (e.g., due to adjustment of contracts). According to a previously conducted expert survey (cf. Reißmann et al., 2020a), the mean substrate increase rate is approx. 13%.	*Production costs per unit*: Disposal costs are assumed to increase proportionally to the 13% increase in substrate amount.
Process water treatment	It is assumed that after anaerobic COD elimination (base case), a further aerobic post-treatment takes place (process water cycle). In addition, a lower pH of 2 (acid addition) is assumed (acidic HTC). However, there is another mass reduction and reduction of the product yield from 11,000 tons to 9,900 tons (assuming the solid residues have dried to dry matter content of 91%).	*Production costs per unit*: Increase of the production costs according to the reduction in mass, whereby reduced transport costs must be included. The cost of process water treatment is increased by 30% of total costs based on own calculations and comparative data of Terranova Energy (Terranova Energy, 2016).
		Mass balance: Reduction of the product yield or mass to be disposed of by 10%.
		Energy balance: The calorific value increases by 4 MJ/kg for acidic HTC. Based on own calculations, the methane potential increases by 18.6 kWh/t fresh matter and therefore flows into the energy balance as a credit note. Exact values for the reduced energy requirement due to the improved drainage properties could not be found. Nevertheless, in order to take the factor into account, a conservative approach of 5% energy saving in process water treatment is applied.
		Pollution of process water: The aerobic post-treatment increases the COD elimination by 10% compared to the base value. Another 10% COD elimination is gained by lowering the pH-value.
System integration	The HTC plant is directly integrated into the waste water treatment plant (WWTP). For the reference technology, this is also assumed based on the current state of the art.	*Distance of plant to suitable substrates*: Since the HTC plant is directly integrated into the WWTP, the distance is reduced to a few meters. Based on the paths on the site of a comparable WWTP, we assume 100 m.
		Production costs per unit: Transport costs from WWTP to HTC are marginal (100 m) and are therefore neglected, which reduces the production costs.

(Continues)

TABLE 3 (Continued)

Scenario factors/descriptors	Assumption for representing the factors	Factor effects on assessment criteria
Nutrient recycling	HTC is carried out in a strongly acidic pH range (acidic HTC), which transfers a large part of the phosphorus (<85%) into the liquid phase, that can then be precipitated from it. This requires the addition of sulfuric acid of more than 12 kg per kg of recycled phosphorus (cf. Blöhse, 2017).	*Production costs per unit*: Based on the available data, we charge a lump-sum increase in costs due to the additional acid demand of 30% for the acidic HTC. In general, however, this additional requirement is already included in the assumptions for process water treatment and the corresponding highly acidic process conditions. Since 30% increase is already taken into consideration due to this, it is assumed that the additional acid requirement for nutrient recycling is also included. In addition, further optimization steps for phosphorus precipitation, which can further reduce the acid demand, are conceivable in the future (cf. Blöhse, 2017, p. 128). Nevertheless, additional process steps, increased environmental requirements, other disposal products, and increased expenses in dealing with sulfur levels in solid and liquid phase are needed. In order to take this into account, a lump sum of 15% additional costs is assumed for the total production costs. *Share of recycled phosphorus*: With HTC leaching a phosphorus recovery rate of up to 85% P_{in} is achieved (Blöhse, 2017).
Learning effects	According to the economic principle of the experience curve (Coenenberg, 1999), the inflation-adjusted (real) unit costs decrease constantly as the cumulative production volume increases. Typically, the costs decrease by a maximum of 30% with a doubling of the cumulative output. In this case, we conservatively assume 15% over 10 years (2020–2029). Therefore, considering that the year 2030 is still ongoing in this analysis, learning effects for this year are excluded. In the base case, learning effects are disregarded.	*Production costs per unit*: The production costs per unit decrease by 15% (conservative learning rate), with a doubling of the cumulative output rate in the period under consideration.

purpose, a Delphi survey was conducted among 51 HTP experts (cf. Reißmann et al., 2018b). The Delphi survey went through two rounds. In the first round, there was a response rate of 53% (27 participants) and in the second round (verification of answers from the first round) of 44% (12 participants). The experts were asked to compare the criteria mentioned in Table 2 (and other evaluation criteria relevant for HTP, but are not included in HTC evaluations) according to their relevance (so-called pair-wise comparisons). Using the Excel solver AHPCalc (Goepel, 2013), the criteria weightings were determined on the basis of the survey results (cf. Reißmann et al., 2020a). In addition, the so-called consistency ratio (C.R.) (Saaty, 1987) was calculated to ensure that the weights are consistent. That means, if A > B > C, then A > C must also apply. According to Saaty, a C.R. < 0.1 represents consistency. The weights and their calculations are part of the data files in Reißmann et al. (2020a). The weighted criteria were then transferred to TOPSIS which evaluates a set of decision alternatives. The so-called virtual best and worst case (i.e., best and worst absolute terms of all criteria values) are used as benchmarks to represent the relative merits of the alternatives (Hwang & Yoon, 1981). Thus, the best alternative in relation to other ones that are part of the analysis is calculated.

To further verify the results, a sensitivity analysis is also executed. The parameters disposal costs, learning rates, and cost-efficiency of process water treatment are varied. The specific variations are part Reißmann et al. (2020a) and Supporting Information Files S1, S2, and S4.

3 | RESULTS AND DISCUSSION

3.1 | Comparative assessment for sewage sludge disposal based on single parameters

Based on the assumptions and calculations described, the results for the base case, the scenario cases and the reference technology are given in Table 4.

TABLE 4 Criteria values for base case, scenarios, and reference technology

Criteria	Unit	HTC-Base	HTC-TA	HTC-LTA	HTC-NA	Reference
Minimizing criteria						
Production costs for solid product	EUR/t[a)]	410.52	401.36	323.39	420.92	329.77
Conversion efficiency/mass balance[b)]	%[c)]	70	63	63	70	100
Distance of plant to suitable substrates	km	20	20	0.1	20	0.1[d)]
Pollution of process water (treated)	mgO$_2$/l	24340	9787	24340	24340	0[e)]
Maximizing criteria						
Energy efficiency/energy balance	%[c)]	49	80	78	49	18
Share of recycled phosphorus	% P$_{in}$	0	0	85	0	0

Underlying data used to create this figure can be found in File S2 and the data repository Reißmann et al. (2020).
[a)] Based on the resulting end product and therefore on different absolute masses.
[b)] In case of disposal, this factor must be minimized, since the mass reduction is then higher. Hence, the amount of waste should be kept to a minimum. If instead the product were sold as a fuel and a profit margin existed, this factor should be maximized.
[c)] Based on dewatered and dried sewage sludge for disposal (dry matter content of 91%).
[d)] The sewage sludge drying usually happens on site, which is why no transport routes are assumed here in the reference case.
[e)] In thermal sewage sludge disposal no HTC comparable liquid phase occurs.

Even without the inclusion of the individual criteria weights, clear differences between the alternatives are obvious. The LTA scenario is the most cost-effective, which is reasoned in learning effects and missing disposal costs. Nevertheless, the difference to the reference technology is relatively low at around €6 per ton.[i] The TA and LTA scenarios each include a 15% learning rate. However, in the TA scenario, the significantly higher investment and operating costs (especially for process water treatment) compared to the base case and the still occurring disposal costs lead to relative high production costs. The NA scenario shows that, despite lower investment costs in simpler plant technology, production costs per unit remain high. This is because of missing learning effects. Due to the increase in disposal costs, this scenario is even worse in production costs than the base case.

Substantial differences are also evident in the mass and energy balances of the alternatives. Since the dried sewage sludge serves as the basis for calculation of the substrate input, the mass conversion of the thermal drying is trivially at 100%. In contrast, all HTC cases lead to a mass reduction, which is considered to be positive because of a reduced disposal volume (e.g., lower transport costs, less specific disposal costs). Energy efficiency is significantly higher in the HTC cases than for thermal sewage sludge drying. This is not surprising since high energy efficiency is one of the key advantages of HTC (cf. Lucian & Fiori, 2017; Wang, Chang, & Li, 2019). Regarding process water pollution, thermal drying has a decisive advantage. Since it does not produce such a by-product, the load value can be set to "0". The reference technology and the LTA scenario are advantageous regarding the distance to suitable substrates, since in both cases the processing of the sewage sludge takes place directly on the WWTP and therefore no transport routes occur. Only the LTA scenario provides a content of recycled phosphorus, as it is the only one that assumes integrated nutrient recycling.

3.2 | Comparative multi-criteria assessment

Although there are some advantages and disadvantages to the cases and scenarios, a clear decision for the optimal alternative is relatively difficult to make, as none of them are convincing in all respects. In addition, the individual criteria have not yet been prioritized. In order to decide which alternative is most advantageous, the criteria may be transferred to the technology assessment tool for HTP. According to the procedure described in Section 2, the TOPSIS efficiency scores presented in Table 5 result accordingly.

The multi-criteria technology assessment shows that the LTA scenario is the preferred alternative in this analysis, followed by the reference technology. In particular, the added value of the multi-criteria analysis, including criteria weighting, is that the relative advantages of the LTA scenario compared to the other HTC scenarios, and the reference case, are very evident now indicated through the high TOPSIS efficiency index. When considering the individual criteria, this strong advantage is not directly recognizable, since, for example, the load of the liquid phase in the LTA scenario is also relatively high.

TABLE 5 TOPSIS efficiency scores for the base case, scenarios, and reference technology

Cases	TOPSIS efficiency	Distance best case	Distance worst case	Rank
HTC-base case	0.14	0.34	0.05	4
HTC-TA scenario	0.27	0.31	0.11	3
HTC-LTA scenario	0.78	0.10	0.36	1
HTC-NA scenario	0.11	0.37	0.04	5
Reference technology	0.59	0.21	0.29	2

Underlying data used to create this figure can be found in File S3 and the data repository Reißmann et al. (2020).

The LTA scenario is probably the most advantageous because it performs best in the key criteria production costs and share of recycled phosphorus, which are both highly weighted. The reference technology is particularly convincing due to the non-occurring process water and the relatively low production costs, which is why it performs quite well. The other three alternatives perform much worse and differ only very slightly to each other. In general, based on the rating, these alternatives are not recommendable.

In the decision-making process, one should first prefer the LTA scenario, whereby this also depends on the framework conditions of the individual decision. For example, if the load of the process water in the LTA scenario is not tolerable for a decision-maker, then the reference technology should be preferred. In that case, however, a higher weighting of the criterion "pollution of process water" would be advisable, or it must be determined a threshold value as K.O. criterion.

The analysis of the modeled case studies on sewage sludge treatment with HTC provides plausible results. It seems reasonable to conclude that only the LTA scenario is advantageous compared to the reference technology, since in particular the lower production costs and the integrated phosphorus recycling represent important advantages. It should be noted, however, that the phosphorus recovery rate in sewage sludge treatment for mass reduction is actually not the target. The target is to achieve a phosphorus content in the remaining solid lower than 20 g of phosphate per kilogram of dry matter (Blöhse, 2017). In this regard, there is a need for further development in the criteria system depending on the objective of the evaluation. In addition, this analysis describes only a modeled example and this is why the results are not transferable. Furthermore, also phosphorus recovery from thermally dried and combusted sludge is possible afterward. This was not included in this case, as the system boundary was set at the delivery of the solid product at the incineration plant. In addition, the aim was to evaluate the system integrated nutrient recycling and not a recycling afterward. However, if the system boundary is set differently and also includes recovery of phosphorus from the ashes, then there would be also a phosphorus recovery rate for thermal drying. Additionally, assuming that legally binding phosphorus recycling from sewage sludge causes a large proportion of the sludge into mono-combustion, it can also be expected that the costs of disposal of the thermal recovery will cease, as the cement industry may be willing to continue to use this substitute fuel in co-combustion. All these factors would change the overall results. However, this requires further assumptions about costs and technology. For example, one could base the recovery of phosphorus from sewage sludge ashes using the so-called Mephrec process, since pilot studies have already been carried out (Reckter, 2019). Hence, further research on this is recommended.

3.3 | Sensitivity analysis

The parameters are only varied for the affected HTC cases. The criteria for the reference technology are kept constant in all analyzes, so that comparability with the initial assessment is ensured. The following assignment to the parameters applies:

- Disposal cost reduction: Basis Case, TA and NA scenarios
- Learning effects: TA and LTA scenarios
- Cost and performance of process water treatment: TA scenario

3.3.1 | Sensitivities for reduced disposal costs

Reducing the disposal costs only influences the production costs for the cases concerned (i.e., base case, TA and NA scenario). The resulting costs are given in Reißmann et al. (2020a) (and also S1 and S4). It should be mentioned, that while in the base case and in the NA scenario the production costs decrease in proportion to the reduction of the disposal costs, this is not the case with the TA scenario. Due to the assumption that the complex process water treatment technology always contributes 30% in addition to the total costs, in this case the costs decrease disproportionately, so that if the disposal costs are completely missing, the production costs of the TA scenario are even higher than in the other two cases. For the reference

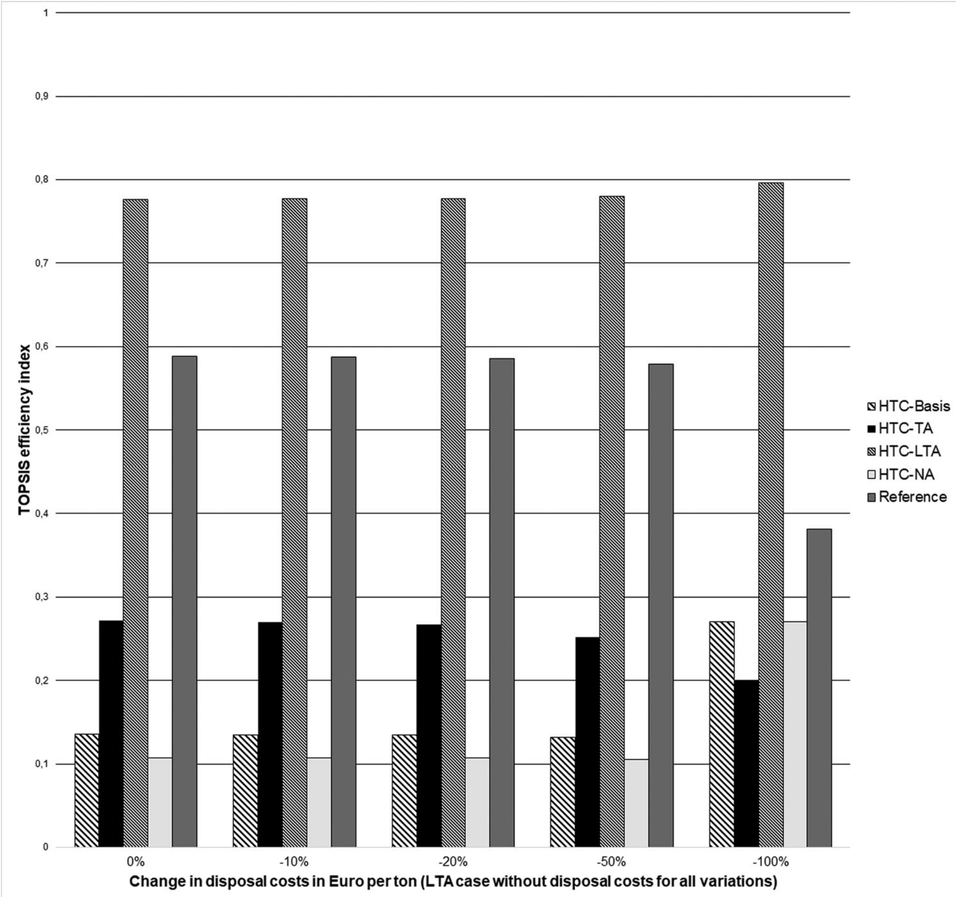

FIGURE 2 TOPSIS efficiency index sensitivities on disposal cost change
Note. HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution.
Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a)

technology, the disposal costs were not varied but instead fully taken into consideration (€80 per ton) as it is assumed that only for HTC disposal cost decrease will occur. In the LTA scenario, the disposal costs were already eliminated for the basis assessment. Transferred to the multi-criteria analysis, the relationship shown in Figure 2 results.

The changes to the initial case (cf. Table 5) in a multi-criteria context are only very slight when reducing the disposal costs. However, if the disposal costs are being dropped, the picture changes significantly. Although the LTA scenario is still most efficient, the gaps of the other scenarios to the reference technology are much lower now. The criteria set of all alternatives is now much clearer, as the distances in the criterion production costs are no longer that strong. When interpreting results from TOPSIS, it is therefore important to consider the entirety of the criteria and their specific weighting and to include all this information into the decision. Basically, it can be stated that by eliminating the disposal costs for the HTC solid product an advantage compared to thermal drying for all alternatives, except the TA scenario, comes closer. Nevertheless, the base case and the NA scenario are still less competitive, also because the non-occurring liquid phase represents a significant advantage of the reference technology.

3.3.2 | Sensitivities for different learning rates

In the case of a variation of the learning rates only the production costs change. For the corresponding cases, the specific values resulting are given in Reißmann et al. (2020a) and S1 as well as S4. For the TOPSIS efficiency indices, the variations according to Figure 3 emerges.

The learning rate has a significant impact on the overall result due to its high cost reduction potential. At lower learning rates in the TA and LTA scenarios, a largely balanced picture emerges, apart from the fact that the high production costs in the TA scenario make it by far the least favorable alternative. It can also be seen that starting at a learning rate of 15%, the LTA scenario makes a strong leap and then represents the most

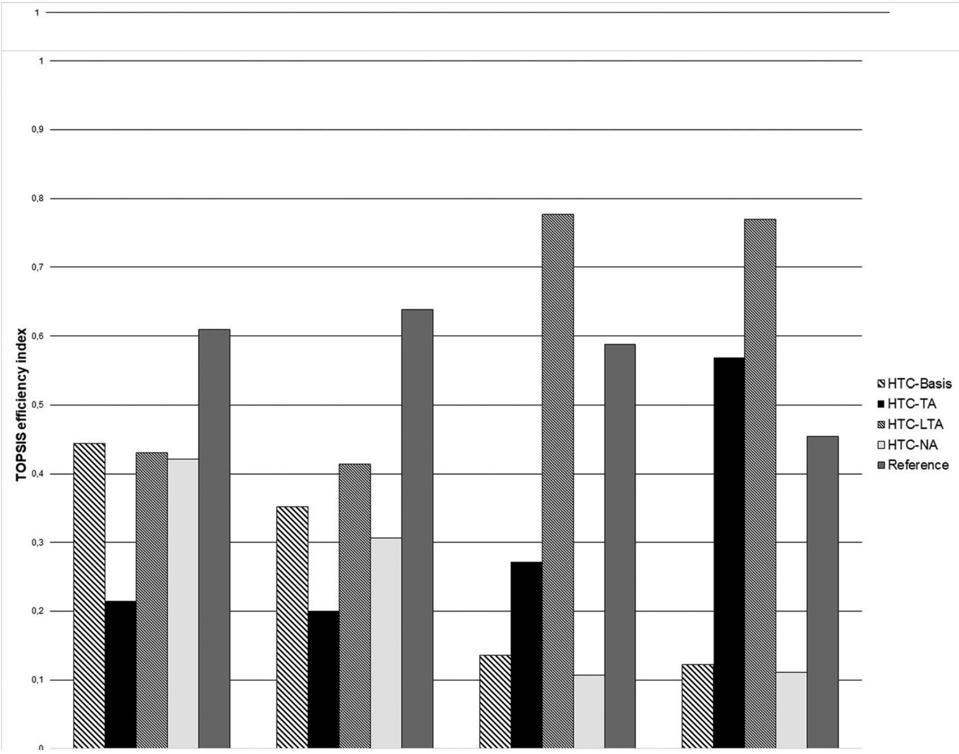

FIGURE 3 TOPSIS efficiency index sensitivities on different learning rates
Note: HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution.
Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a).

advantageous alternative. At a learning rate of 25%, TA and LTA scenarios are most beneficial. The efficiency indices of the other two HTC cases are decreasing steadily, while the reference case is more robust against an increasing learning rate in the TA and LTA scenario, but also loses relatively high in the efficiency index given the high learning rate of 25%. In general, it can be stated that with a learning rate of 25%, the HTC alternatives in which action is taken are competitive to the reference technology regarding the overall assessment.

3.3.3 | Sensitivities for cost-efficient process water treatment

Regarding the costs and performance of process water treatment, only the TA scenario is relevant, since only this scenario assumes an additional process water treatment. For the sensitivity analysis, it is first assumed that the performance is increased with additional measures by 50%. However, in the first variant this also leads to 50% additional costs for this cost factor (proportional cost efficiency). In the second variant, again, a performance of 50% is assumed, but with a disproportionate cost increase of 60% and 80% (disproportionate cost increase). In the third variant, the cost increase is assumed to be constant at 50%, but a higher treatment performance of 60%, 80%, and 98% is assumed (disproportionate performance increase). The sensitivities for the production costs and process water treatment performance of the TA scenario are also part of S1 and S4. Figure 4 shows these variants in a multi-criteria context.

None of the considered constellations achieves a significant change in the overall result. Only for "proportional change," it can be observed that the NA scenario and base case improve significantly and become more advantageous than the TA scenario, which now has significantly higher production costs. The other sensitivities show a largely stable picture, the changes are very small. Obviously, the cost increases for process water treatment—even with the highest performance (98%)—always overcompensate all other criteria and lead to the result, that the TA scenario is the worst alternative in all variants. Further considerations in TOPSIS show that even with constant costs in the TA scenario and maximum treatment performance no advantage can be achieved. With a cost reduction of 17% to the initial costs and a consistent highest treatment performance of 98%, the TA scenario is advantageous compared to the reference technology, but is still less favorable than the LTA scenario. Only with a production cost reduction of at least 39% the TA scenario will be advantageous compared to all cases in a multi-criteria context. It is therefore advisable to make process water treatment more cost-effective or to extract and market any by-products (e.g., carbon) that result from the liquid phase.

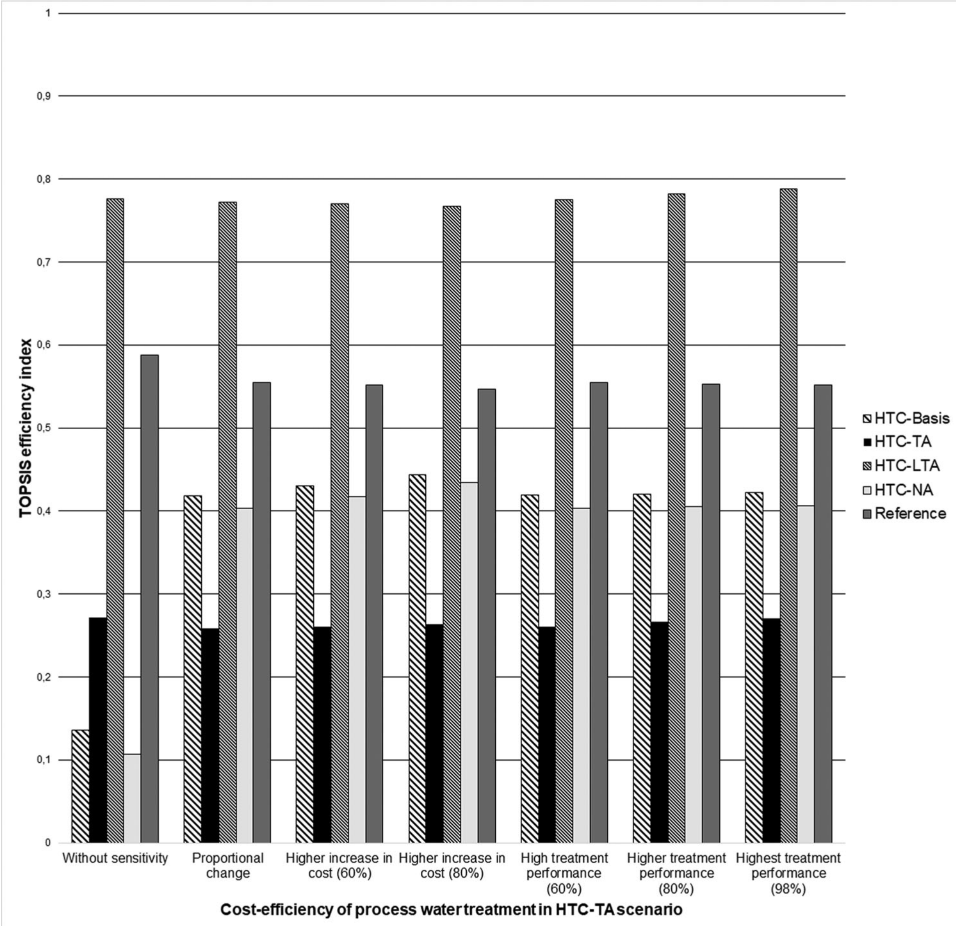

FIGURE 4 TOPSIS efficiency index sensitivities on different costs and treatment performances of process water treatment
Note: HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution.
Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a).

3.3.4 | Effects on TOPSIS efficiency assuming best parameter combination

Combining the best of the above-mentioned parameters, the LTA scenario dominates (0.79), followed by the TA scenario (0.56) and the reference technology (0.43). The following is assumed:

- Highest cost savings in TA scenario due to learning effects of 25% (assuming that disposal cost increase is overcompensated and thus no included additionally).
- Highest cost savings in LTA scenario due to learning effects of 25%.
- Highest process water treatment performance in TA scenario of 98% with cost savings due to learning effects.
- No disposal costs in base case.

In particular, the learning effects have the strongest effects, since they greatly reduce production costs. However, the high treatment performance in the TA scenario is not sufficient to make this scenario advantageous compared to the LTA scenario, which in turn illustrates the strong dominance of production costs as a decision-making criterion within this case study.

3.4 | Central findings based on MCA and the sensitivity analysis

The production costs have a very strong influence on the overall result, since they are included in the evaluation with almost 40% weight. However, regarding the background of the economic viability of such niche technologies, this is definitely conclusive. Cost-effective competition with the reference technology is achieved only in the HTC-LTA scenario, but the performance of the process water treatment is insufficient for this case, which is a major barrier. The higher production costs in the other HTC cases always make them unfavorable to the reference technology, even when the process water treatment performance is very high (e.g., 98% in the TA scenario). Basically, only the LTA scenario tends to be competitive with the reference technology, whereby the assumption that there are no disposal costs is largely unrealistic from a current perspective. The TA scenario only becomes competitive when the production costs fall sharply (17–39% cost reduction) and at the same time the process water treatment performance significantly increases. According to this analysis, the base case and the HTC-NA scenario are not competitive in any way. Therefore, they cannot be considered as viable developments for HTC sewage sludge disposal in Germany.

According to this study, the most important parameters for an overall comparability are the production costs, the process water treatment performance, and the degree in phosphorus recycling. In terms of energy and conversion efficiency, HTC is superior to the reference technology in all cases, but this is not sufficient to achieve an overall benefit. The future technological development of sewage sludge HTC should therefore concentrate on the most cost-efficient process water treatment, further potentials for reducing the production costs (e.g., reduction of energy costs through heat waste recovery), and suitable concepts for system-integrated nutrient recycling. In particular, the necessary process water treatment—to tap the exploitation potential and to ensure the legally prescribed treatment targets—represents a point already mentioned many times, which is also considered in other studies as a decisive factor for the techno-economic implementation (e.g., Fettig et al., 2018). Regarding production costs, Lucian and Fiori (2017), for example, cite a range of €157–200 per ton as competitive for the energetic use of the pelleted solid product from HTC. Comparable costs imply this study, whereby the energetic use of the product was not considered. In this study, depending on the specific conditions, production costs per ton HTC solid product of less than €325 are recommended. In the TA scenario, a benefit compared to the reference case was achieved at less than €333 per ton and increased process water treatment performance of 98%. A benefit compared to all alternatives for the TA scenario was achieved for less than €245 per ton and corresponding high process water treatment performance.

Whether HTC represents a suitable alternative to sewage sludge incineration is disputed even beyond the questions on costs and process water treatment. The solid product tends to be unsuitable for the existing stock of sewage sludge incinerators in Germany, as they are designed for higher water contents. According to the current state of knowledge, there is no reference plant for mono-incineration of the highly dewatered sewage sludge from HTC (cf. Remy & Stübner, 2015). In order to increase the quality of the product, qualitative substrates are needed. Often, however, sewage sludge does not represent such a qualitative substrate, which is why HTC research and development may need to address other residues (Brosowski et al., 2016).

In principle, the results should be further validated, for example, by further sensitivity studies, the analysis of other case constellations or by the inclusion of additional parameters (e.g., GHG emissions). The technology assessment tool can be a good aid for this, whereby the interpretation of the results must always be considering the overall context of criteria. A verbal argumentative discussion of the results is therefore obligatory.

4 | CONCLUSION AND IMPLICATIONS

By means of a multi-criteria analysis of sewage sludge HTC on the basis of different scenarios, their competitiveness compared to thermal sewage sludge treatment was considered. The results of this analysis largely confirm the current problems in the field of using HTC for sludge disposal and show that HTC is only advantageous to the thermal drying under very favorable conditions.

The main results of this study can be summarized as follows:

1. Production costs, process water treatment performance, and the proportion of phosphorus recovered have the greatest impact on HTC competitiveness compared to conventional processes.
2. According to this study, the competitive production costs are less than €325 per ton of HTC end product, whereby only the delivery of the product up to mono-combustion and not beyond was considered.
3. The performance of process water treatment should be maximized while keeping costs as minimal as possible. It is recommended to extract by-products from the liquid phase (e.g., carbon) for further sales in order to counteract the high costs.
4. Further potential for reducing production costs lies in system integration (e.g., by using waste heat, considering possible alternatives for outlet products) and the recycling of other nutrients such as nitrogen. However, further research is necessary here, especially based on valid data which is currently not available.
5. A supportive legal framework that in particular allows the use of the HTC product as an energy source can contribute to further cost savings, for example, by no longer incurring disposal costs at the incineration plant. It also ensures greater legal certainty for the actors.
6. Learning effects also ensure substantial cost reductions, whereby this simple business assumption is not based on exact measures but is due to this type of business scenario analysis.

Since the results apply only to the modeled case examples presented here, a generalizability and transferability is not given. Hence, there is a need for further case studies to underpin the results. An application to real plants is stimulated, although in Germany currently no corresponding

HTC plants exist in industrial continuous operation and a corresponding analysis would have to make an assumption-based scaling. Nevertheless, such analyzes are important in order to be able to carry out real tests on the basis of existing technological cases.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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[i] Throughout the document, the term ton is to be equated with metric ton.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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